

**Institut für Natur- und Ressourcenschutz  
Christian-Albrechts-Universität zu Kiel**

**Water Resources in Lake Tana Basin:  
Analysis of hydrological time series data and  
impact of climate change with emphasis on  
groundwater, Upper Blue Nile Basin, Ethiopia**

**Dissertation**

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## **Abstract**

Ethiopia is a source region of the Nile River and famous for its water resources potential. The available annual average water per person per year is estimated to be 1575 m<sup>3</sup>. However, the water is not available at the time and place where it is required due to the large spatial and temporal variations in rainfall and a lack of the required technology and infrastructure. Therefore, the Ethiopian government has selected different areas as development corridors to achieve its development and transformation agenda. Among others, the Lake Tana basin is one of the development corridor areas primarily due to its groundwater and surface water potential. The total catchment area of the Lake Tana basin is 15,321 km<sup>2</sup>. The climate is influenced by the movement of the inter-tropical convergence zone (ITCZ) resulting in a high seasonality of rainfall with a rainy season between June and September. However, the scientific understanding of the hydrologic response to intensive agriculture, the interconnection of groundwater and surface water, and future perspectives of the water availability under global climate change is limited. Therefore, the main aim of this study is to improve our understanding of past, present, and future hydrologic conditions in three sub catchments of the Lake Tana basin, Gilgelabay, Gumara, and Ribb. Different sequential methodological approaches were followed to achieve the research objective. The spatial and temporal patterns of the hydrologic conditions during the last half century were analysed based on long-term hydrological and climatological data between 1960 and 2015 using the Mann-Kendal trend test, auto- and cross-correlation, and Tukey multiple mean comparison tests. Furthermore, the semi-distributed hydrologic model SWAT (Soil and Water Assessment Tools) and an integrated surface water and groundwater model (SWAT-MODFLOW), which is a hybrid of the SWAT model and MODFLOW (a three-dimensional finite difference groundwater model) were applied. The hydrologic models were calibrated and

validated to minimize uncertainties. The mid-term and long-term development of the 21st century was modelled using projected rainfall and temperature data of an ensemble of regional climate models under the scenarios of Representative Concentration Pathways RCP4.5 and RCP8.5.

Results from the long-term time series analyses revealed that the hydrologic condition in the study area is highly variable both at spatial and temporal scales. The rainfall and streamflow patterns showed high seasonal anomalies. Most of the peak rainfall and streamflow events occur during the wet season (June to September); all other months are characterized as dry season (October to May) with less rainfall and low flow. The statistical tests indicated that the overall annual rainfall in the Lake Tana basin did not change significantly, but there are slight changes. The streamflow increased significantly for Gumara and Megech, the Lake outflow decreased during the 2000s to 2010s. The lake level dropped abruptly since the beginning of 2000s and did not recover yet.

Results of the SWAT model also proved that the hydrologic condition in the study area is highly variable both spatially and seasonally. The dominant agricultural crops showed variable influences on the major water balance components. Groundwater recharge was relatively high on agricultural land covered by cereal crops like teff and millet, whereas surface runoff was significantly enhanced on cultivated land covered by leguminous crops like peas. Compared to Gilgelabay and Ribb, Gumara catchment showed more surface runoff. Groundwater discharge contributes substantial amount to the streamflow in all the three catchments.

The interconnectivity between the groundwater and surface water was assessed with the coupled hydrologic model SWAT-MODFLOW. The groundwater-surface water

interactions showed significant spatial and temporal variabilities. There were also different dynamics of groundwater-surface interaction between the three catchments. The annual exchange rate was dominated by flow from the aquifer to the stream in the Gilgelabay catchment, while bidirectional flow was observed in the Gumara and Ribb catchments. Compared to the annual groundwater-surface water interaction, the daily interaction was more dynamic.

Possible future changes of the major water balance components in the Lake Tana basin were simulated with the two greenhouse gas concentration pathways, RCP4.5 and RCP8.5. The expected increases of the ensemble mean temperature in the study area are likely to be higher than the global average, while the expected changes in rainfall are not significant. Relative to the baseline average, the ensemble mean actual evapotranspiration are likely to decrease in both catchments for both periods. Likewise, groundwater contribution to the streamflow is likely to decrease in both future periods under both scenarios. Unlike actual evapotranspiration and groundwater contribution to the streamflow, surface runoff is expected to increase significantly for both periods under both scenarios. This is due to the expected high variability of rainfall intensity and seasonality during the two future periods.

Modelling and time series analyses enhances our understanding of past, current and possible future hydrologic conditions in the study area. Overall, outputs revealed that considerable spatio-temporal changes had occurred for the hydrology of Lake Tana Basin during the last half century and more changes are also expected in the future. Consequently, the results of this PhD dissertation can contribute to develop future water management plans in the region and beyond.

## **Zusammenfassung**

Äthiopien ist eine Quellregion des Nils und bekannt für sein großen Wasserressourcen. Die verfügbare Wassermenge pro Person und Jahr wird auf durchschnittlich 1575 m<sup>3</sup> geschätzt. Das Wasser ist jedoch aufgrund der großen räumlichen und zeitlichen Schwankungen der Niederschläge und aufgrund des Mangels von erforderlicher Infrastruktur und Technologie nicht zu der Zeit und an dem Ort verfügbar, an dem es benötigt wird. Um ihre Entwicklungs- und Transformationsagenda zu erreichen, hat die äthiopische Regierung verschiedene Regionen im Land als Entwicklungskorridore ausgewählt. Unter anderem ist das Einzugsgebiet des Tanasees aufgrund seiner Ressourcen von Grund- und Oberflächenwasser Teil des Entwicklungskorridors. Das gesamte Einzugsgebiet des Tanasees hat eine Fläche von 15 321 km<sup>2</sup>. Das Klima der Region wird durch die Verlagerung der innertropischen Konvergenzzone bestimmt, die in einer ausgeprägten Saisonalität des Niederschlags mit einer Regenzeit von Juni bis September resultiert. Das wissenschaftliche Verständnis bezüglich der hydrologischen Reaktion auf die intensive Landwirtschaft, der Verbindung von Grund- und Oberflächenwasser und der zukünftigen Wasserverfügbarkeit unter dem Einfluss des globalen Klimawandels ist jedoch begrenzt. Daher ist das Ziel dieser Dissertation, die vergangenen, gegenwärtigen und zukünftigen hydrologischen Bedingungen in drei Teileinzugsgebieten des Tanasee-Einzugsgebiets, den Teileinzugsgebieten Gilgelabay, Gumara und Ribb, besser zu verstehen. Um das Forschungsziele zu erreichen, wurden nacheinander verschiedene methodische Ansätze verfolgt. Die räumlichen und zeitlichen Muster der hydrologischen Bedingungen während des letzten halben Jahrhunderts wurden auf der Grundlage langfristiger hydrologischer und klimatologischer Daten zwischen 1960 und 2015 unter Verwendung des Mann-Kendal-Trendtests, der Auto- und Kreuzkorrelation und der Tukey-Mehrfachmittelwertvergleichstests analysiert. Darüber

hinaus wurden das hydrologische Modell SWAT (Soil and Water Assessment Tools) und ein integriertes Oberflächen- und Grundwassermodell (SWAT-MODFLOW), das eine Kopplung zwischen den Modellen SWAT und MODFLOW (ein dreidimensionales Finite-Differenzen-Grundwassermodell) darstellt, angewandt. Die hydrologischen Modelle wurden kalibriert und validiert, um Unsicherheiten zu minimieren. Die mittel- und langfristige Entwicklung des 21. Jahrhunderts wurde anhand von prognostizierten Niederschlags- und Temperaturdaten eines Ensembles regionaler Klimamodelle unter den Szenarien ‚repräsentativer Konzentrationspfade‘ RCP4.5 und RCP8.5 modelliert.

Die Ergebnisse aus den Zeitreihenanalysen zeigten, dass der hydrologische Zustand im Untersuchungsgebiet sowohl auf räumlicher als auch auf zeitlicher Ebene sehr variabel ist. Die Niederschlags- und Abflussmuster wiesen hohe saisonale Anomalien auf. Die meisten Spitzenwerte der Niederschlags- und Abflussereignisse treten während der Regenzeit (Juni bis September) auf. Alle anderen Monate sind als Trockenzeit (Oktober bis Mai) durch weniger Niederschlag und geringen Abfluss gekennzeichnet. Die statistischen Tests ergaben, dass sich die jährliche Gesamtregenmenge im Tanasee-Einzugsgebiet nicht wesentlich verändert hat, aber es dennoch leichte Veränderungen gibt. Der Abfluss nahm in den Teileinzugsgebieten Gumara und Megech deutlich zu. Hingegen nahm der Abfluss des Sees von den 2000er zu den 2010er Jahren ab. Der Seewasserspiegel fiel seit Anfang der 2000er Jahre abrupt und erholte sich seitdem nicht mehr.

Die Ergebnisse des SWAT-Modells zeigten ebenfalls, dass der hydrologische Zustand im Untersuchungsgebiet sowohl räumlich als auch jahreszeitlich sehr variabel ist. Die vorherrschenden landwirtschaftlichen Kulturen zeigten variable Einflüsse auf die wichtigsten Wasserhaushaltskomponenten. Die Grundwasserneubildung war auf

landwirtschaftlich genutzten Flächen, die mit Getreidekulturen wie Teff und Hirse bedeckt waren, relativ hoch, während der Oberflächenabfluss auf landwirtschaftlich genutzten Flächen, die mit Leguminosen wie Erbsen bedeckt waren, signifikant erhöht war. Im Vergleich zu Gilgelabay und Ribb zeigte das Gumara-Einzugsgebiet mehr Oberflächenabfluss. Der Grundwasserabfluss trägt in allen drei Einzugsgebieten in erheblichem Maße zum Abfluss bei.

Die Wechselwirkung zwischen Grundwasser und Oberflächenwasser wurde mit dem gekoppelten hydrologischen Modell SWAT-MODFLOW untersucht. Sie zeigte eine signifikante räumliche und zeitliche Variabilität. Zwischen den drei Einzugsgebieten gab es eine unterschiedliche Dynamik der Interaktion von Grundwasser und Oberflächenwasser. Im Gilgelabay-Einzugsgebiet wurde der jährliche Austausch durch die Fließrichtung vom Aquifer zum Fließgewässer dominiert, während in den Einzugsgebieten Gumara und Ribb bidirektionale Flüsse beobachtet wurden. Im Vergleich zur jährlichen Interaktion von Grundwasser und Oberflächenwasser war die tägliche Interaktion dynamischer.

Mögliche zukünftige Veränderungen der wichtigsten Wasserhaushaltskomponenten im Tanasee-Einzugsgebiet wurden mit den beiden Szenarien ‚repräsentativer Konzentrationspfade‘ RCP4.5 und RCP8.5 simuliert. Der Anstieg der Ensemble-Mitteltemperatur im Untersuchungsgebiet ist höher als der globale Durchschnitt, während die Veränderung der Niederschläge nicht signifikant ist. Relativ zum Durchschnitt des Referenzlaufs (baseline) zeigen die Ensemble-Mittelwerte, dass die tatsächliche Evapotranspiration in beiden Einzugsgebieten für beide Perioden abnimmt.

Ebenso nimmt der Anteil des Grundwassers am Abfluss in beiden zukünftigen Perioden und in beiden Szenarien ab. Im Gegensatz zur tatsächlichen Evapotranspiration und zum Grundwasseranteils am Abfluss wird sich der Oberflächenabfluss in beiden Szenarien für beide Zeiträume voraussichtlich deutlich erhöhen. Dies ist auf die hohe Variabilität der Niederschlagsintensität und Saisonalität während der beiden zukünftigen Perioden zurückzuführen.

Modellierung und Zeitreihenanalysen verbessern das Verständnis der vergangenen, aktuellen und möglichen zukünftigen hydrologischen Bedingungen im Untersuchungsgebiet. Insgesamt zeigen die Ergebnisse, dass sich die Hydrologie des Tanasee-Einzugsgebiets im letzten halben Jahrhundert räumlich und zeitlich erheblich verändert hat und auch in Zukunft deutliche Veränderungen zu erwarten sind. Folglich können die Erkenntnisse dieser Dissertation zur Entwicklung von zukünftigen Wassermanagementplänen in der Region und darüber hinaus beitragen.



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# **1. General introduction**

## **1.1. Background**

Global economic development and human welfare are often limited by the availability and quality of water. The rapid growth of the world population and economic development are increasing the global water demand (Kundzewicz et al. 2007). Agriculture, food production and water are inseparably linked (Watts et al. 2015). Water use in agriculture accounts for 70% of the global total water use (Hatfield 2014) and has a significant impact on the water balance components. Agricultural land use affects the hydrologic cycle in terms of the partitioning of rainfall between evapotranspiration, runoff, and groundwater recharge (Watts et al. 2015). The quality of surface water and groundwater has generally declined in recent decades mainly due to an increase of agricultural and industrial activities (Parris 2011). Moreover, climate change studies show that surface water and groundwater resources are expected to decrease significantly in the future in most dry subtropical regions (IPCC 2014). This could cause water stress and intensive competition for water among sectors (Björklund 2001). The effect of climate change is expected to be more severe on the social-ecological systems in developing countries since they have the lowest capacity to adapt (Dile et al. 2018). Besides this, the adverse effects of climate change on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land-use change, and urbanization (Kundzewicz et al. 2007). Thus, providing sufficient quantity and acceptable quality of water to the world's human population is one of the preeminent challenges of the 21st century (Tarhule 2017). As a result, availability and sustainable management of water and sanitation for all are part of the United Nations' sustainable development goal (Brookes and Carey 2015).

Ethiopia is one of the countries with the largest increase in population between 2019 and 2050 (UN 2019). The agriculture sector plays a central role in its economy. About 85% of all employment relies on it (FAO, 2014). The sector is dominated by small-scale farms that are

characterized by rain-fed mixed farming. Crop production accounts for about 60% of the agricultural outputs (Gebre-Selasie and Bekele 2012). The crop productivity varies with the availability of water and water use in agriculture. Although Ethiopia is perceived as the water tower of Eastern Africa, temporal variability (seasonality) and uneven spatial distribution of water resources remain a primary challenge. Availability of water is highly dependent on the seasonality and inter-annual variability of rainfall and streamflow. Most of the rivers have their peak flows during the rainy months (June-September) and cause a flooding effect on areas of their surroundings. On the other hand, flow volumes are considerably low during dry months (October-May) (Berhanu et al. 2014). The temporal variability of rainfall and streamflow extremes are linked to low frequency climate processes centred over the mid-latitudes of the Pacific basin (Taye et al. 2015) causing widespread, devastating droughts and floods that occur every 3–5 years (World Bank 2006). Crop failure or a decrease in agricultural production, and livestock perishing are the major consequences of drought that frequently occur in the country. Hence, the overall national GDP is frequently affected by the quantity and timing of rainfall. To overcome this widespread problem, understanding the effect of agricultural crops on the hydrologic cycle is important. (World Bank 2006). Therefore, a better understanding of the historical, present, and future hydrologic situation is essential to meet the water resources management challenges.

Ethiopia has nine major rivers, twelve big lakes, and large reserves of groundwater. Lake Tana is the largest fresh water lake in the country. While the country has considerable annual renewable freshwater potential, its agricultural crop production still depends on seasonal rainfall, and the national safe water supply access coverage is only 76.7% (MoWE 2015). Because of siltation problems in rivers and reservoirs, resulting in substantially higher treatment and maintenance costs of the water schemes, groundwater is the primary source of water for urban and rural water supply (World Bank 2006). However, excessive groundwater

abstraction has led to groundwater depletion and pollution and thus challenges water resources management in the country (MoWE 2015). These developments also have negative effects on the flow of groundwater fed streams, the health of the ecosystems, and the depths of local groundwater tables (de Graaf et al. 2014). The complete drying up of Haramaya Lake in Eastern Ethiopia since 2005 is an example for the consequences of decreasing groundwater levels due to over-pumping of groundwater for agriculture and household use (Abebe et al. 2014).

The Upper Blue Nile basin, which originates from Lake Tana, covers an area of 199,812 km<sup>2</sup>, i.e. 20% of Ethiopia (Dile et al. 2016). Past studies in the Upper Blue Nile Basin (e.g., Elshamy et al. 2009; Setegn et al. 2010; Polanco et al. 2017; Woldesenbet et al. 2017) have reported that water resources in the basin are not being managed adequately due to the hydrological variability, climate change, land use changes, rapid population growth, soil erosion, and deforestation. Additionally, studies of hydrological and climate change came to different and contradictory conclusions. For instance, Tessema et al. (2010) reported that the mean annual streamflow at the Lake Tana outlet (Abay) was significantly increasing during 1964-2003. On the other hand, Tekleab et al. (2013) found a decrease in the mean annual streamflows of Gilgelabay and Ribb sub-catchments (inflows) of the Lake Tana Basin during 1973-2003 and 1973-2005. Similarly, climate change studies of the Upper Blue Nile basin have shown different results of future rainfall at basin or sub-basin scale (Taye et al. 2015). Elshamy et al. (2009) reported that changes in total annual projected rainfall for the late 21st century in the Upper Blue Nile basin vary between -15% to +14%, while Setegn et al. (2010) found no significant change. Kim et al. (2009) analyzed the changes in projected rainfall and temperature for six GCMs and the ensemble mean of the GCMs showed an increase of 11% of the mean annual rainfall for the 2050s. Another climate change impact study carried out by Beyene et al. (2010) in the Nile River basin, based on 11 GCMs, showed an increase in rainfall for the early 21st century (2010-2039) and a decrease during the mid (2040-2069) and late (2070-2099)

century. Taye et al. (2011) also investigated the impact of climate change on hydrological extremes of the Lake Tana basin. In this study, both decreasing and increasing rainfall and streamflow are expected. In general, past climate change studies on the Upper Blue Nile basin and its sub-basins showed contradictory results of the projected rainfall changes, because most of the studies did not use ensemble approach.

The Lake Tana basin (Figure 1) supports the livelihood of more than 3 million people, and it is well known for its water resource potential. Being the sub-basin of Upper Blue Nile basin, Lake Tana basin is dominated by intensive agriculture with a high impact on the basin hydrologic regime and ecological condition (Setegn et al. 2010). Moreover, Lake Tana Basin became a focus area of many scientific studies because of its national and international importance. These include water balance analyses of different sub-catchments including the lake (Derib 2013; Tegegne et al. 2013; Dessie et al. 2015), hydrological modeling with emphasis on surface water (eg. Dessie et al. 2014; Worqlul et al. 2015; Polanco et al. 2017), hydrometeorological trend analyses (e.g. Gebrehiwot et al. 2014; Mengistu and Lal 2014), climate change impact studies (e.g. Koch and Cherie 2013; Teshome 2016), land use/cover change impact on hydrologic responses (e.g. Gumindoga et al. 2014; Woldesenbet et al. 2017), implications of water harvesting intensification on upstream–downstream ecosystem services and water availability (e.g. Dile et al. 2016), and groundwater and hydrogeology (e.g. Yitbarek et al. 2012; Awange et al. 2014).

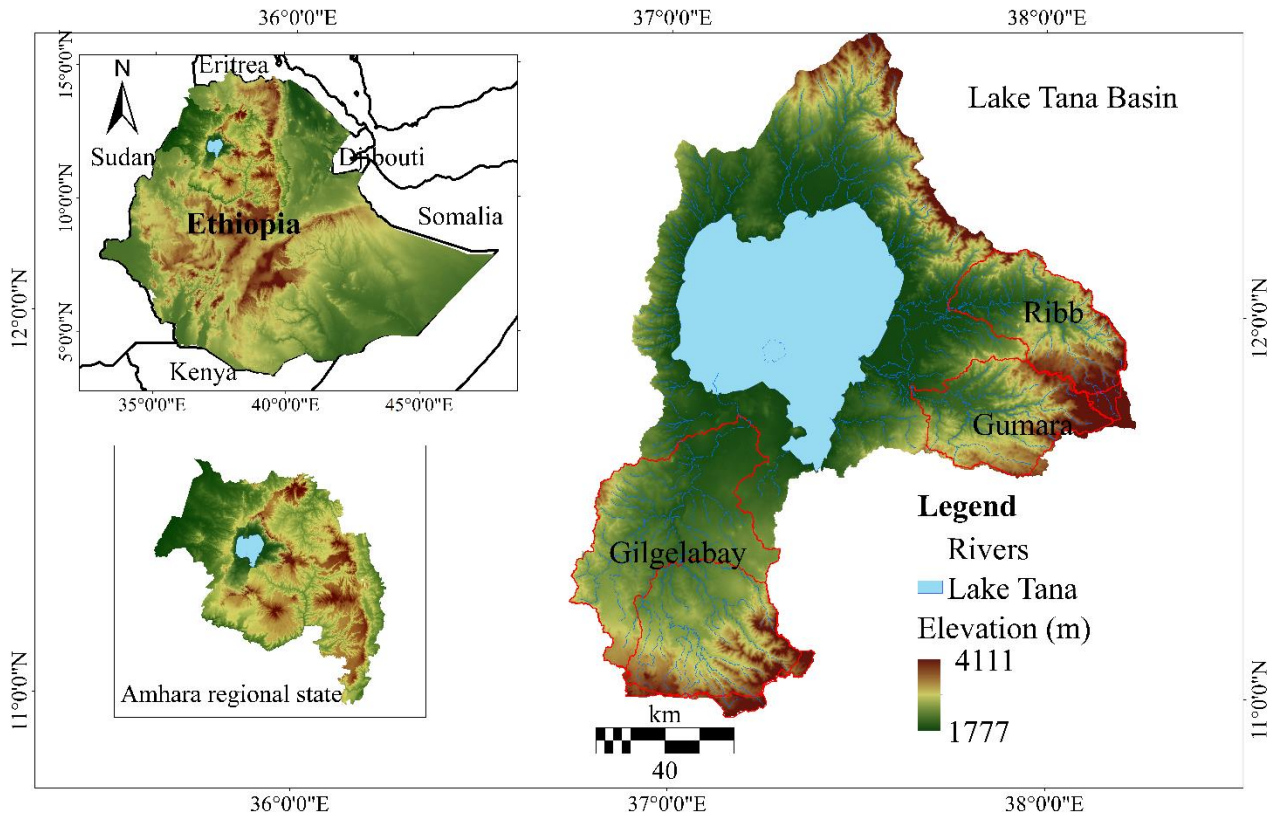


Figure 1-1: Location Map of Lake Tana Basin with reference to Amhara regional state and Ethiopia

## 1.2. Analysis of hydrometeorological time series

The analysis of historical patterns of hydrometeorological variables is an integral part of water resource development programs (Gebrehiwot et al. 2014). Good quality rainfall and streamflow data are required for hydrological as well as climate change studies and can often be taken from observation networks (Stahl et al. 2010). Hence, time series analysis of hydrometeorological data is a crucial prerequisite for hydrological modelling studies. Statistical hydrology has emerged as a powerful tool for analysing hydrologic time series of both surface water and groundwater systems during the past three decades (Machiwal and Jha 2006). Trend detection, test of homogeneity (stationarity), seasonality, and decadal tests are the most frequently used statistical tests in hydrology. Gradual change over time which is consistent in direction (monotonic) or an abrupt shift (breakpoint) at a specific point in time on time series records is



known as trend (Meals et al. 2011). A stationary or homogeneous time series is one whose statistical properties such as mean, variance, autocorrelation, and other statistical properties are all constant over time, otherwise it is called non-stationary. The existence of trends in hydro-climatic variables such as rainfall, temperature, humidity, evapotranspiration, and streamflow are an indication of climatic variability and climate change (Birsan et al. 2005; Rashid et al. 2015). Investigating the existence of trends is a widely recognized statistical approach to detect non-stationarity in time series (Taye et al. 2015). Trend detection can be applied in all-time series of hydrometeorological variables such as rainfall, temperature, humidity, wind speed, and streamflow.

### **1.3. Hydrological modeling**

Hydrological models are relevant tools to better land and water management practices (Palanco et al. 2017). The use of physically based hydrologic models has been increasing over time because of their capabilities to incorporate physical processes of the system. The Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998, Arnold and Fohrer 2005) is one of the most widely applied river basin-scale hydrologic model. Because of its adaptability for both large and small scale catchments and continuous improvement, researchers in different fields have identified SWAT as one of the most intricate, dependable, and computationally efficient models (Neitsch et al. 2011; Palanco et al. 2017). The model is capable of simulating spatially distributed water balance components based on hydrological response units (HRUs).

Likewise, application of the SWAT model in Ethiopian watersheds is expanding over time. Among others, the following are a few case studies that applied SWAT as their modelling tool. Setegn et al. (2009, 2011) used SWAT2005 to test its applicability in the Lake Tana Basin and applied to evaluate the past and future water balance situation of the basin. With this study, the authors concluded that SWAT model was capable to model the hydrologic al processes of the Lake Tana basin. Their water balance results showed that actual ET accounts more than 60%

of the basin hydrologic processes, and the groundwater contribution to the streamflow varies between 40% and 60%. Dile et al. (2013) used the SWAT model to study the effects of climate change on hydrological responses of Gilgelabay catchment. According to this study, the monthly mean volume of runoff the catchment tends to increase significantly (up to 135%) for the mid and long-term of the 21st century. Dile et al. (2016) used SWAT2012 for their study to investigate the implications of intensive water harvesting on upstream–downstream ecosystem services in the Lake Tana basin. In these studies, they found that intensification of water harvesting in the basin would increase low flows and decrease peak flows. They also found a reduction in the amount of sediment yield that leave the catchment. Polanco et al. (2017) applied SWAT model to investigate the effect of discretization on its performances in the entire Upper Blue Nile Basin under. Their finds showed that increasing the number of sub-basins would affect the magnitude of streamflow and other water balance components and the authors suggested increasing the number of sub-basins is important to improve the performances of SWAT model in the basin. Another hydrological assessment study by Desta and Lemma (2017) in the Lake Ziway watershed, Rift valley, Ethiopia used SWAT as their modelling tool, and their finds showed that the annual base flow is decreasing, while actual ET is increasing over time. Overall, all studies proved that SWAT models is capable to simulate the hydrological processes in Ethiopia as a whole and in Upper Nile basin in particular. However, all of studies considered the water balance components at the outlets of the study catchments ignoring spatial distributions of water balance components. In addition to this, the seasonal and spatial variability of the hydrological components under different vegetation cover condition are missed.

#### **1.4. Groundwater dynamics and climate change**

Aquifers are the largest storage of global freshwater: more than two billion people rely on groundwater (Cuthbert et al. 2019). Groundwater (GW) accounts for one third of all freshwater

withdrawals of the world, supplying an estimated 36%, 42% and 27% of the water for domestic, agricultural and industrial purposes, respectively (Taylor et al. 2013). Although GW is vulnerable to depletion, it is being consumed faster than it is being naturally replenished (Rodell et al. 2009; Sutanudjaja et al. 2011). The rapid population growth, expansion of irrigation agriculture, and economic development globally increased the water demand, and leads to water stress in several parts of the world (Wada et al. 2010). Groundwater levels and fluxes are controlled by a dynamic interplay between recharge and discharge, with a variety of controls and feedback loops from climate, soils, geology, land cover and human abstraction (Cuthbert et al. 2019). According to Abbaspour et al. (2015), the quality and quantity of GW in Europe are under heavy pressure and water levels have decreased. Compared to surface water, groundwater responds more slowly to changes in meteorological conditions (Bovolo et al. 2009). As a result, the laws governing groundwater rights are still static even in developed countries (Rodell et al. 2009). This aggravates overexploitation of GW worldwide and very pronouncedly in arid regions (Hashemi et al. 2015). Higher standards of living, demographic changes, land and water use policies, and other external forces are increasing the pressure on groundwater resources. In Ethiopia, 80% the national water demand is covered from groundwater source (Kebede 2012). The total annual aquifer recharge is estimated to be more than 30 billion cubic meter (Berhanu et al. 2014; Kebede 2010). Due to the infancy institutes and research capabilities in the country, our knowledge about the groundwater recharge, groundwater-surface water connection, and aquifer properties is limited (Berhanu et al. 2014). **Therefore, combined use of groundwater (GW) and surface water (SW), understanding the groundwater (GW) - surface water (SW) interaction, and investigating the effect of climate change on GW are urgent issues that need to be addressed.**

So far, a number of models are developed to study the interaction between GW and SW. According to (Zhou and Li 2011), 1966 was a year when numerical models were applied for

the first time to simulate steady state regional flow patterns of hypothetical aquifer systems. Since then, numerous physically based models were evolved (eg. MODFLOW, Harbaugh et al. 2000) and applied to improve understanding of process dynamics. Interests of developing and using coupled land surface and subsurface models are growing. Coupling of MODFLOW with SWAT model is a recent advancement. Bailey et al. (2016) developed the coupled SWAT-MODFLOW model that was upgraded later into the graphical user interface model SWATMOD-Prep (Bailey et al. 2017). Ehtiat et al. (2018) integrated SWAT, MODFLOW, and MT3DMS to investigate how SW conditions affect the quality of the GW system in a non-coastal aquifer. Similarly, Park et al. (2019) developed a QGIS-based graphical user interface SWAT-MODFLOW model for Middle Bosque River Watershed in central Texas. These advancements of coupled model development are derived due to the deficiencies associated with surface water and groundwater models. Although SWAT model has wide range of application history, it has a limitation to simulate groundwater dynamics below threshold depth of 6m (Neitsch et al., 2011; Guzman et al. 2015; Shao et al. 2019). It uses the hydrologic response units (HRUs) as its smallest spatial computation unit where there is no exchange of water between different HRUs (Chunn et al. 2019), and the HRUs are lack of geolocation that result spatial disconnection (Guzman et al. 2015; Bailey et al. 2016). Additionally, SWAT has a limitation to capture groundwater dominated low flows (Pfannerstill et al. 2014). The MODFLOW also has its own limitation to simulate the surface hydrologic processes because its subroutines are designed to simulate flow processes occurring in the saturated zone such as GW recharge, GW discharge, and pumping (Harbaugh 2005). Thus, application of coupled model like SWATMODFLOW (Bailey et al. 2016, Bailey et al. 2017) will provide additional information such as volumetric exchange rates between the surface water and groundwater, groundwater discharge and stream seepage areas, deep percolation to the aquifer, and distributed groundwater head. Thus, use of such coupled hydrological model is important in

regions like Ethiopia where there is a knowledge gap about the groundwater-surface water interaction.

Uncertainties related to water resources management are growing due to the effect of climate change (Abbaspour et al. 2015). For this reason, a lot of research efforts are advancing overtime to understand the influence of climate change on water resources system. For example, Givati et al. (2019) studied the impact of climate change on streamflow of at the upper Jordan River based on an ensemble projected regional climate data. In this study, the authors used projected rainfall and temperature datasets of nineteen regional climate models (RCMs) from the CORDEX project for RCP4.5 and RCP8.5 scenarios. Marx et al. (2018) studied how global warming alter the low flows in Europe based on multi-model ensemble under three concentration pathways (RCP2.6, RCP6.0, and RCP8.5). Past climate change impact studies primarily focused on surface water, and only a few of them addressed the effect of climate change on groundwater (Goderniaux et al. 2009; Kidmose et al. 2013). However, there are recent advancement towards investigating the impact of climate change on groundwater (e.g., Cuthbert et al. 2019a studied the global patterns and dynamics of climate-groundwater interactions; Cuthbert et al. 2019b investigated resilience of groundwater to climate variability in in sub-Saharan Africa). Chunn et al. (2019) studied the impacts of climate change and water withdrawal on the GW-SW interactions in West-Central Alberta using the integrated SWAT-MODFLOW model. The potential impact of climate change on GW varies both temporally and spatially. Both a decrease and increase of groundwater levels are reported. Ali et al. (2012) reported that the GW system in the south-western Australia was less affected by the future drier climate than the surface water system, but projected water tables are expected to decline in all areas under a drier climate where perennial vegetation was present and able to intercept recharge or use groundwater directly. An increase of the GW table is expected for future climate conditions in irrigation-dominated areas in the Oliver region of the south Okanagan,

British Columbia (BC), Canada (Toews and Allen 2009). A climate change impact study by Döll (2009) revealed an increase of groundwater recharge in northern latitudes, while 30–70% decrease is expected in semi-arid zones, including the Mediterranean, north-eastern Brazil and south-western Africa between 1961–1990 and 2041–2070. A recent study conducted by Cuthbert et al. (2019) in sub-Saharan Africa indicated that the multiyear continuous GW levels decline in Tanzania, Namibia, and South Africa, while long-term rising trends were reported for Niger. Another climate change impact study carried out in the Ethiopian Tekeze basin (Kahsay et al. 2018) based on the Coordinated Regional Climate Downscaling Experiment (CORDEX) Africa datasets for Representative Concentration Pathways (RCPs) of RCP 2.6 and RCP 4.5 scenarios showed decreases in the projected GW recharge by 3.4% for RCP 2.6 and 1.3% for RCP 4.5, respectively. Overall, study results on the effect of climate change on GW show that the magnitude and scale of influences vary from one geographic location to another, and very few studies are available for Africa in general and Ethiopia in particular. **This indicates that the hydrological processes controlling groundwater recharge and sustainability, and sensitivity to climate change in Africa are poorly understood and cause high uncertainties for future water resources management and planning (Cuthbert et al. 2019b).** Hence, more research efforts are required with regard to climate change impact on GW to minimize the uncertainties related to future water management and planning in Africa.

### **1.5. Statement of the problem and research questions**

The major challenge of Ethiopian water resources management is the very high water variability in combination with marked rainfall seasonality (World Bank 2006). Moreover, hydrologic processes in the Lake Tana basin are not yet fully understood due to its complex biophysical processes and scarcity of hydrometeorological data (Leggesse and Beyene 2017). Consequently, this is dissertation was designed to answer multiple research questions that are related to water resources of the Lake Tana basin based on observed hydrological and climate

time series data during the last half-century, and simulated outputs from a physically based hydrologic models for current and future time periods.

Tesemma et al. (2010) and Tekleab et al. (2013) studied the trends of hydrometeorological variables within the upper Blue Nile basin. They used the Mann-Kendall, Pettitt, and Sen's t-tests for trend analysis and found a significant increase in discharge during the rainy season (June to September) at Bahir Dar, Kessie, and El Diem gauging stations, whereas seasonal and annual basin-wide average rainfall trends were not significant. On the one hand, Mengistu et al. (2014) reported an increasing trend on the annual total rainfall of the upper Blue Nile basin for the years between 1980 and 2010 (35mm per decade), but the change was not statistically significant. On the other hand, the basin-wide annual rainfall of upper Blue Nile basin showed an insignificant decreasing trend during 1954 to 2004 (Tabari et al. 2015). Gebrehiwot et al. (2014) investigated statistical changes on the long-term hydrology of catchments within upper Blue Nile and found that the hydrological regime of the upper Blue Nile Basin during 1960–2004 was stable. However, there the low flow decreased in some watersheds and increased in others. Generally speaking, past hydrometeorological trend studies conducted so far in Ethiopia are not conclusive and some are only conducted at the macro scale (Asfaw et al. 2018); findings are not in agreement. This implies that additional research effort is needed to advance our understanding of hydrometeorological condition in the country and in Lake Tana basin. For this reason, the first research question of this PhD dissertations is formulated as follows:

**were there significant long-term changes (1960-2015) in rainfall, streamflow, and lake outflow time series observable in the Lake Tana basin?**

The Lake Tana basin is known for its national and international importance. It has significant national importance because the government of Ethiopia has identified it as a potential area for irrigation and hydropower development, which are vital for food security and economic growth in the country (Tegegne et al. 2017). Similarly, the Lake Tana basin is of international

importance as it is a headwater source of the Nile River and an area of high biodiversity (Setegn et al. 2010). As a consequence, several hydrological models from simple conceptual to more advanced physically and semi-physically based hydrological models have been applied to understand hydrological processes and the water balance of the Lake Tana basin (Dile et al. 2018). However, most of the past hydrological studies focus on the water balance at basin outlets and lack detailed mapping of water balance components on a spatial basis. In addition, the hydrologic studies do not investigate the hydrologic mass balance in relation to vegetation types (van Griensven et al. 2012). Although the SWAT model was used to investigate the effect of land use change on the hydrology of the basin, none of the papers explicitly addressed the specific effects of crops on the water fluxes. Here, the second key purpose of this PhD dissertation is to answer the following research question:

**how do the major water balance components vary on spatial and seasonal basis under different agricultural crops and land use/cover classes?**

According to the Ethiopian government growth and transformation plan, agriculture irrigated from GW sources is expected to cover 2 million hectares by 2020 (Kebede 2012). Due to its proximity to the point of demand, GW provides 90% of the domestic water supply, 95% of the industrial use, and a small proportion of irrigation water demand. In general, 80% of the total national water supply comes from GW (Kebede 2018). Previous hydrological studies focused on the surface water use and hydrologic balance and do not adequately address issues of GW, particularly in the context of combining SW–GW models in the Lake Tana Basin. Dile et al. (2018) reviewed research in the upper Blue Nile basin. According to this review, application of integrated hydrologic models is missing, as most studies have focused on single model applications to estimate a single output such as streamflow or sediment loss at the basin outlet. Consequently, the authors recommended that future research should focus on the application



of coupled models to predict multiple outcomes across multiple spatial and temporal scales in the basin. Additionally, Chebud and Melesse (2009), who applied a numerical model to investigate the groundwater flow system in the Gumara catchment, identified a research gap on the spatial and temporal distribution of percolation in the Gumara catchment in particular, and in Lake Tana Basin in general. A climate change impact study carried out by Taye et al. (2015) in the Lake Tana basin reported that low flows are expected to decline by up to -61% under the A1B and B1 emission scenarios for 2050s. Consequently, it is assumed that more GW will be used to overcome the freshwater constraint in Ethiopia in general and in the Lake Tana Basin in particular. From this, we can understand that demand of groundwater for agricultural, domestic, and industrial uses in the future are expected to increase. However, our knowledge about the GW-SW flow dynamics on the spatio-temporal basis for the current and future condition is limited. Hence, answering the following two key research questions will enhance our understanding about the GW-SW flow dynamics and future water availability in the Lake Tana Basin.

- **Do the groundwater and surface water systems interact with each other and how does the behaviour of GW-SW interaction vary in space and time?**
- **How will future climate change affect the major water balance components of the Lake Tana basin?**

## **1.6. Thesis structure**

The PhD thesis is divided into six chapters. The first chapter is the general introduction that includes background information, state of the art and motivation of the research that explains the derived research questions. The second chapter deals with time series analysis of the rainfall and streamflow data of the past half century. In the third chapter, hydrologic changes under the influence of different agricultural crops are addressed. The fifth chapter focuses on the hydrologic flow dynamics of groundwater and surface water conditions in the Lake Tana Basin.

Anticipated changes of hydrology due to climate change are discussed in chapter five. The last chapter focusses on the general discussion and conclusion of the overall outcomes of the dissertation.

## **2. Statistical analysis of rainfall and streamflow time series in the Lake Tana Basin, Ethiopia**

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## **Abstract**

This research focuses on the statistical analyses of hydrometeorological time series in the basin of Lake Tana, the largest freshwater lake in Ethiopia. We used autocorrelation, cross-correlation, Mann-Kendall, and Tukey multiple mean comparison tests to understand the spatiotemporal variation of the hydrometeorological data in the period from 1960 to 2015. Our results show that mean annual streamflow and the lake water level are varying significantly from decade to decade whereas the mean annual rainfall variation is not significant. The decadal mean of the lake outflow and the lake water level decreased between the 1990s and 2000s by 11.34 m<sup>3</sup>/s and 0.35 m, respectively. The autocorrelation for both rainfall and streamflow were significantly different from zero indicating that the sample data are non-random. Changes in streamflow and lake water level are linked to land use changes. Improvements in agricultural water management could contribute to mitigate the decreasing trends.

Keywords: hydrometeorology; autocorrelation; cross-correlation; Tukey's test; temporal variation.

## **2.1. Introduction**

Management and analysis of time series data are integral parts of hydrological and climate studies. Good quality data are required for climate change detection as well as for hydrological studies and can often be taken from observation networks (Stahl et al. 2010). Data can be accessed in different formats from different organizations and should be managed properly. There are a number of tools for data management, analysis and interpretation e.g. SPSS, R and Matlab which are capable of accessing data from many different sources and a smaller number of systems capable of handling data management, analysis and interpretation (Horsburgh and Reeder 2014). Different kinds of data analysis methods can be chosen for different research objectives. Time series analysis of rainfall and streamflow is crucial as it is a prerequisite for further using the data in e.g. hydrological modelling studies. A time series is defined as a sequence formed by the values of a variable at increasing points in time that may be composed of a random element and a non-random element (Matalas 1967). It is said to be random if the values of the time series are independent of each other, otherwise it is non-random. A non-randomly distributed sequence repeats some of the information contained in previous values. The nature of hydrolometeorological data can be investigated by testing their randomness, trend and association with other variables such as biophysical and socio-economic variables. For instance, the interaction of hydrological variables with land use changes has been studied by Wagner and Waske (2016) and Wagner et al. (2016). Persistence of a trend and its magnitude in hydrological time series data were studied by different scholars (e.g. Thomas & Pool 2006, Stahl et al. 2010, Hawtree et al. 2017, Wagner et al. 2018). A number of hydrological studies were carried out in Ethiopia in general, in Lake Tana Basin in particular (Setegn et al. 2008; Alemayehu et al. 2009; Alemayehu et al. 2010; Dargahi and Setegn 2011; Koch and Cherie 2013; Gebremicael et al. 2013; Mehari, K.A. et al. 2014; Dessie et al. 2015; Woldesenbet et al. 2017). For instance, Woldesenbet et al. (2017) studied the impact of land

use land cover change on streamflow of Tana and Beles sub-basins in Ethiopia. This research revealed that the average annual water yield, the average annual baseflow and average annual basin percolation decreased gradually, to the contrary the average annual surface runoff increased. These changes are associated with expansion of cultivation land and the shrinkage in woody shrub from 1986 to 2010. Koch and Cherie (2013) studied the impact of future climate change on hydrology and water resources management of the whole Upper Blue Nile Basin. Streamflow records over the time period 1970-2000 of Abay River at Eldiem gauging station close to the Ethio-Sudan border were analysed using Mann-Kendall and the seasonal Mann-Kendall test and the result showed a significantly increase trend (Koch and Cherie 2013). Although many research studies were done on various hydrological and environmental issues in the Blue Nile basin, very few of them were focused on long-term trends of hydrometeorological variables at catchment level (Tekleab et al. 2013). Furthermore, there were conflicting results on the trends of hydrometeorological time series in the Blue Nile basin. For instance, Tessema et al. (2010) reported that the mean annual streamflow at the Lake Tana outlet (Abay) was significantly increasing during 1964-2003. On the other hand, Tekleab et al. (2013) found a decrease of the mean annual streamflows of Gilgilebay and Ribb sub-catchments (inflows) of the Lake Tana Basin during 1973-2005/2003. This indicates that analyses on one long term time series alone might not be sufficient to understand hydrometeorological variabilities. Moreover, most of the hydrometeorological variability and trend analysis studies were carried out using Mann-Kendall (MK) and Pettitt tests as the only methods of investigations. On top of that, hydrometeorological trend analysis studies conducted so far in Ethiopia are not conclusive and some are conducted at macro scale, underlining the need for further research (Asfaw et al. 2018). As Ethiopia is strongly dependent on agriculture with a highly variable hydrology, its agricultural yield is frequently affected by droughts and famines. The United Nations Children's Fund (UNICEF) reported that the 2015-2017 drought

caused by El-Nino effect is one of the worst droughts in decades (UNICEF 2016). Consequently, improved understanding of the patterns of historical observed hydrometeorological time series on the local scale using different time spans is crucial for water use and management. Since the study area is highly dynamic with respect to hydrology and most of the previous studies were carried out on the macro-scale, attention should be given to hydrometeorological changes on the local scale. Therefore, this study aims at conducting a thorough analyses of the temporal and spatial variation of long-term rainfall, streamflow and lake water level in the Lake Tana Basins over the period (from 1960 to 2015) on decadal, annual, seasonal, and daily time scales. To this end multiple statistical methods such as Tukey multiple mean comparison tests, autocorrelation, cross-correlation and MK test are used to characterize the decadal and seasonal changes, dependency of events on the adjacent ones with respect to time, response of streamflow to rainfall events and existence of trends. Accordingly, the research questions were the following:

- Are the rainfall/ streamflow events related to their preceding ones?
- Are the time series data random or non-random?
- Are rainfall and streamflow events cross-correlated?
- Do decadal, annual and seasonal rainfall, streamflow and lake water levels show significant changes over time?

## **2.2. Materials and Methods**

### **2.2.1. General overview of the study area**

Lake Tana is the largest freshwater lake in Ethiopia and the third largest in the Nile Basin. The catchment area of the lake at its outlet is 15,321 km<sup>2</sup>. About 20% of the catchment area is covered by Lake Tana (Alemayehu et al. 2010, Kebede et al. 2006). The catchment is approximately 84 km long, 66 km wide and is located in the country's north-west highlands.

Its topography is very diverse with an altitude ranging from 1322 m to 4111 m above sea level (m.a.s.l.). The lake has a surface area of 3,156 km<sup>2</sup> and extends between 10.95°N to 12.78°N latitude and from 36.89°E to 38.25°E longitude at an average altitude of 1,786 (m.a.s.l.), (Tegegne et al. 2013). The lake is shallow with a maximum depth of 15 m and characterized by a steep slope at the borders and by a flat bottom (Kebede et al. 2006). Lake Tana is the source of the Blue Nile River (McCartney et al. 2010). It contains about 50% of the country's fresh water. More than 40 rivers and streams flow into Lake Tana, but 93% of the water comes just from four major rivers: Gilgelabay, Gumara, Ribb and Megech (Setegn et al. 2008; Alemayehu et al. 2010). The mean annual inflow is estimated to be 158 m<sup>3</sup>/s (Alemayehu et al. 2010). The only surface outflow from the lake is the Blue Nile (Abay) River with an annual flow volume of 4 billion m<sup>3</sup> measured at Bahir Dar gauge station (lake outlet in Fig. 1).

Rainfall records in the basin show strong spatial and temporal variability as the basin is influenced by the inter-tropical convergent zone (ITCZ) and a heterogeneous topographic nature. The position of the ITCZ is the most dominant factor that controls the amount of summer rainfall in the basin. In the Lake Tana basin, rainfall has high seasonal variability. July, August & September are wet months with the highest amounts of rainfall as the ITCZ position is in the northern hemisphere. June and October are transition months of wet and dry seasons. November, December, January, February, and March belong to the dry season. April and May are months with little rainfall. A similar classification applies to the West Sahel region (Lucio et al. 2012). There is also high spatial variability of annual, seasonal and monthly rainfall amounts in the study area because of small changes of the location of the ITCZ (Gleixner et al. 2016; Woldesenbet et al. 2017). Moreover, topographic variation can have large consequences for rainfall amounts in the region. The amount of annual rainfall is directly related to elevation above mean sea level; high rainfall is corresponding to the highlands, whereas low rainfall is measured in the lowlands (Fig. 5).



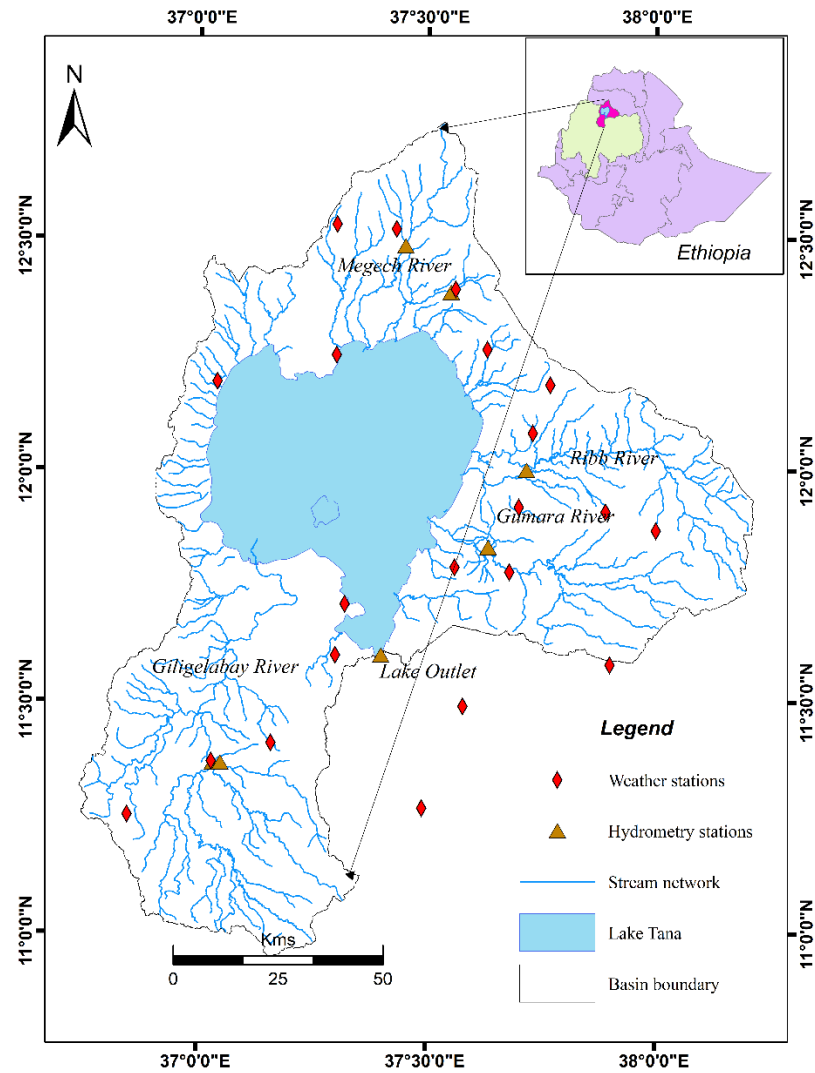


Figure 2-1: Location map and major tributaries of Lake Tana including river gauging & weather stations

### 2.2.2. Data Analysis

Several years of daily hydrometeorological data records from 1960 to 2015 were collected. The streamflow and lake water level records were gathered from the Department of Hydrology, Ministry of Water, Irrigation and Electricity of the Ethiopian Government (MoWIE 2016) and the meteorological data were collected from the National Meteorological Service Agency (NMA 2016). There are many weather stations in the study area, but only 18 stations that have relatively good continuity were considered for the analysis (Fig. 1 & 5).

#### 2.2.2.1. Statistical Methods

For this study, basic statistical analysis techniques including the Tukey's multiple mean comparisons, a nonparametric Kendall tau and seasonal Mann-Kendal tests as well as auto- and cross-correlation analyses were used. These methods were chosen to understand the variability of the hydrometeorological data over time as well as to characterize and detect the relation between the hydrometeorological variables.

*Tukey's ("honestly significant difference" or "HSD"):* Tukey's multiple comparison test is a useful statistical method that can be used to determine which means amongst a set of means differ from the rest (Bates 2010). For the first time, Tukey's HSD test was applied in the Lake Tana Basin to understand the variability of mean values of river discharge and lake water level on a decadal basis. Streamflows of Gilgelabay, Gumara, Ribb, Megech, outflow from the Lake Tana, and the lake water level were considered. The decadal analyses of streamflows at the aforementioned stations and the lake water level were made by partitioning the recorded data into different decades to understand the change of annual mean values overtime. The time series data were split into the following decadal groups: 1960-1979, 1980-1989, 1990-1999 and 2000-2014. In this case, the null hypothesis assumed was that the annual mean values of streamflows and lake water level were time invariant (same for different decades) and the alternative hypothesis was that annual mean values differed with time. The 5% level of significance was considered in all of these analyses. The anova and TukeyHSD functions available in the base package of R were used to calculate the statistical values (R Core Team 2017).

*Autocorrelation:* Autocorrelation analysis provide information about persistence of a variable by calculating the linear dependency of successive values over a given period. Mangin (1984) first applied autocorrelation to karstic systems in the Pyrenees, France, to measure the persistence of a signal in the series (Duvert et al. 2015). It is also commonly used to determine

if the data series is random or non-random (e.g. Matalas 1967; Modarres et al. 2007; Gautam et al. 2010; Duvert et al. 2015). Autocorrelation coefficients of the rainfall and streamflow events were calculated using equation (1) (Duvert et al. 2015). Furthermore, following to (Matalas 1967), who refer to the Anderson (1942) for the test of significance of the autocorrelation coefficient (acf) to a given probability level was tested based on equation (2).

$$r_k = \frac{\frac{1}{N} \sum_{i=1}^{N-k} (x_i - \bar{x})(x_{i+k} - \bar{x})}{\delta^2} = \frac{\sum_{i=1}^{N-k} (x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=1}^N (x_i - \bar{x})^2} \quad (1)$$

$$\tilde{r}_k = \frac{-1 \pm t_{\alpha(\sqrt{N-k-1})}}{N - k} \quad (2)$$

where  $r_k$  is the acf at lag  $k$ ,  $\bar{x}$ , is arithmetic mean of the observation,  $t_\alpha$  is the standard normal variate corresponding to a probability level  $\alpha$ ,  $\tilde{r}_1$  is the upper and lower bounds and  $N$  is the series length. The  $r_k$  value calculated by equation (1) could be compared with the corresponding value calculated using equations 2 for significance test. If the value calculated on equation 1 is greater than values on equations 2, the  $r_k$  seems to be significantly different from zero and the sample observations are dependent on their preceding events at a given time lag  $k$  (Matalas 1967). Therefore, the null hypothesis ( $H_0$ ) and alternative hypotheses ( $H_a$ ) tests of this study were the following:

$H_0$ : events of the daily rainfall, streamflow and lake water level time series were not dependent on their preceding events at time lag  $-k$ . In other words the autocorrelation coefficient at lag  $k$  is not beyond or below the upper and lower bounds and the data were random. The alternative assumption considered was the reverse one i.e. events of the daily rainfall and streamflow time series were dependent to their preceding events at time lag  $k$ . In other words the autocorrelation coefficient at lag  $k$  is out of the upper and lower bounds and the data were non-random.

*Cross-Correlation*: Cross-correlation is the correlation between two time series shifted relatively in time. The method has been widely applied in diverse fields (Chenhua 2015).

Lagged correlation is important in studying the relationship between time series for two reasons. First, one series may have a delayed response to the other series, or perhaps a delayed response to a common stimulus that affects both series. Second, the response of one series to the other series or an outside stimulus may be “smeared” in time, such that a stimulus restricted to one observation causes a response at multiple observations. Detailed mathematical equations are explained in (Duvert et al. 2015). Here we used cross-correlation of rainfall versus streamflow.

Autocorrelations are symmetrical functions (value at lag  $k$  equals value at lag  $-k$ ). In contrast, the cross-correlations are asymmetrical functions. The cross-correlation function is described in terms of “lead” and “lag” relationships. Equation (3) applies to  $y_t$  shifted forward relative to  $x_t$ . With this direction of shift,  $x_t$  is said to be “lead”  $y_t$ . This is equivalent to saying that  $y_t$  “lags”  $x_t$ . A negative value for  $k$  in equation (3) is a correlation between the  $x$ -variable at a time before  $t$  and the  $y$ -variable at time  $t$ . For instance, if  $k=-1$ , the cc value would give the correlation between  $x_{t-1}$  and  $y_t$  (Chatfield 2004).

$$\frac{\sum_{i=1}^{N-k}(x_i - \bar{x})(y_{i+k} - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2 \sum_{i=1}^N (y_{i+1} - \bar{y})^2}} \quad [k = 0 \pm 1, \pm 2, \dots, \pm(N-1)] \quad (3)$$

where  $N$  is the series length,  $\bar{x}$  and  $\bar{y}$  are the sample means, and  $k$  is the lag.

Pairwise cross-correlations of streamflow with the corresponding regional rainfall of each sub basin were carried out. Cross-correlation (cc) tests were carried out for rainfall versus streamflow based on the following null and alternative hypotheses tests stated as follows:

$H_0$ : the daily streamflow and catchment rainfall time series are not correlated significantly or the correlation coefficients at time lag  $k$  between daily streamflow and rainfall is not significantly different from zero.

Ha: the daily streamflow and catchment rainfall time series are correlated significantly or the correlation coefficients at time lag  $k$  between daily streamflow and rainfall is significantly different from zero.

*Kendall tau and seasonal Mann-Kendall tests:* The Kendall and seasonal Mann-Kendall tau tests are nonparametric statistical tests used for detecting trends in time series data (Thomas and Pool 2006). The tests were applied for rainfall, the lake water level and streamflow time series under the following null ( $H_0$ ) and alternative ( $H_a$ ) hypotheses:

$H_0$ : the streamflow, rainfall and lake water level time series data are showing neither an upward nor a downward trend.

$H_a$ : the streamflow, rainfall and lake water level time series data are showing either an upward or a downward trend with significant change.

## **2.3. Results and discussion**

### **2.3.1. Rainfall analysis**

Record lengths of the rainfall data vary from one station to the other stations. The maximum record length is available at Enjabara station which started recording in 1954. About 5.4% of the rainfall data are missing values. The rainfall in the study area has a unimodal pattern with a peak in July or August (Fig. 2). Moreover, the rainfall data shows high spatial and temporal variability. Most of the rainfall frequencies lay below the median values. Data values which are out of the range of  $[Q1 - 1.5 * (Q3 - Q1), Q3 + 1.5 * (Q3 - Q1)]$  ( $Q1$ = first quartile and  $Q3$ = third quartile) are suspected as outliers (Thomas and Pool 2006; Li et al. 2016). About 15 of the stations have mean rainfall values greater than the third quartile which indicates that mean values are biased to the maximum values.

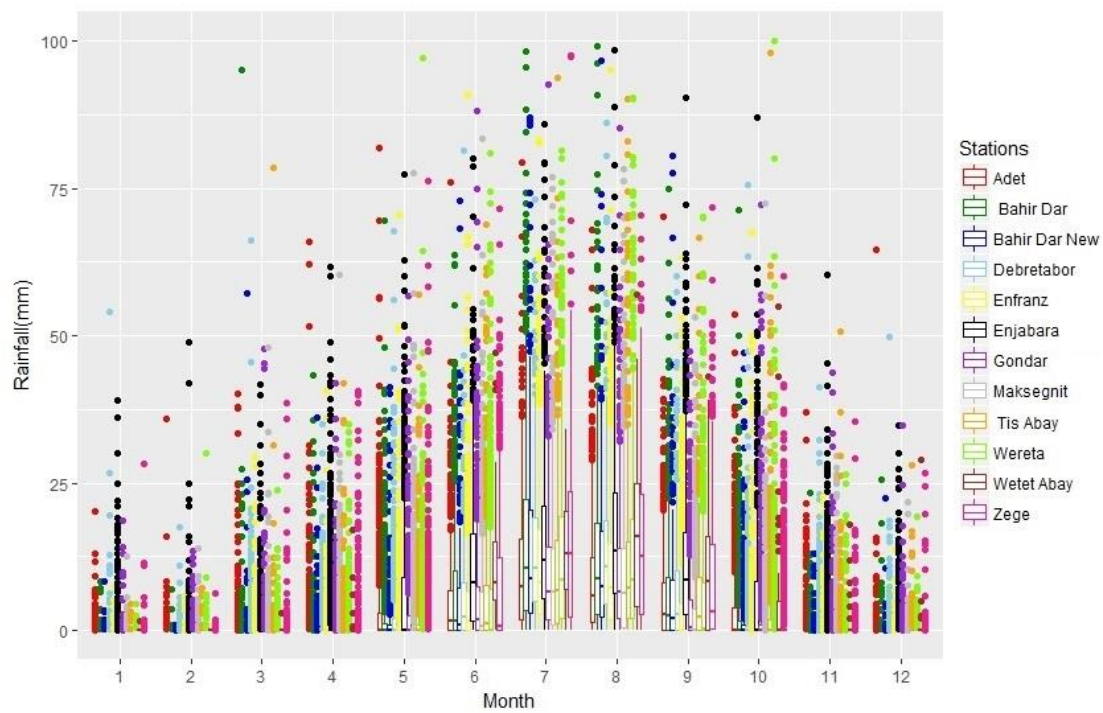


Figure 2-2: A boxplot showing monthly rainfall plots of stations in Lake Tana Basin. The dots indicate outliers outside the interquartile ranges.

### 2.3.1.1. Rainfall lag time correlation

The overall pattern of the correlogram shows a gradual decrease as the lag time increases (Fig. 3). The values range from 0.31 to 0.7. Wereta station has the maximum (approximately 0.7) lag day one autocorrelation coefficient. Even though these coefficients are decreasing when lag time is increasing, all values are beyond the upper bound of the 95% confident interval. The lower and upper bounds were computed using Anderson's formula (equation 2). According to Matalas (1967), a time series exhibiting nonsignificant values of autocorrelation coefficient is not necessarily random since autocorrelation coefficient of order greater than one, if significant, would indicate a lack of randomness. But a data series exhibiting significant values of autocorrelation coefficient indicate non-randomness. Therefore, as the autocorrelation coefficient values are statistically significantly different from zero, they indicate that the rainfall series is characterized by a non-random distribution and linear dependency of successive values over a given period (Matalas 1967; Modarres et al. 2007; Gautam et al. 2010). The non-random distribution of rainfall maybe explained by prevailing weather conditions and large scale transport of water vapour in the atmosphere.

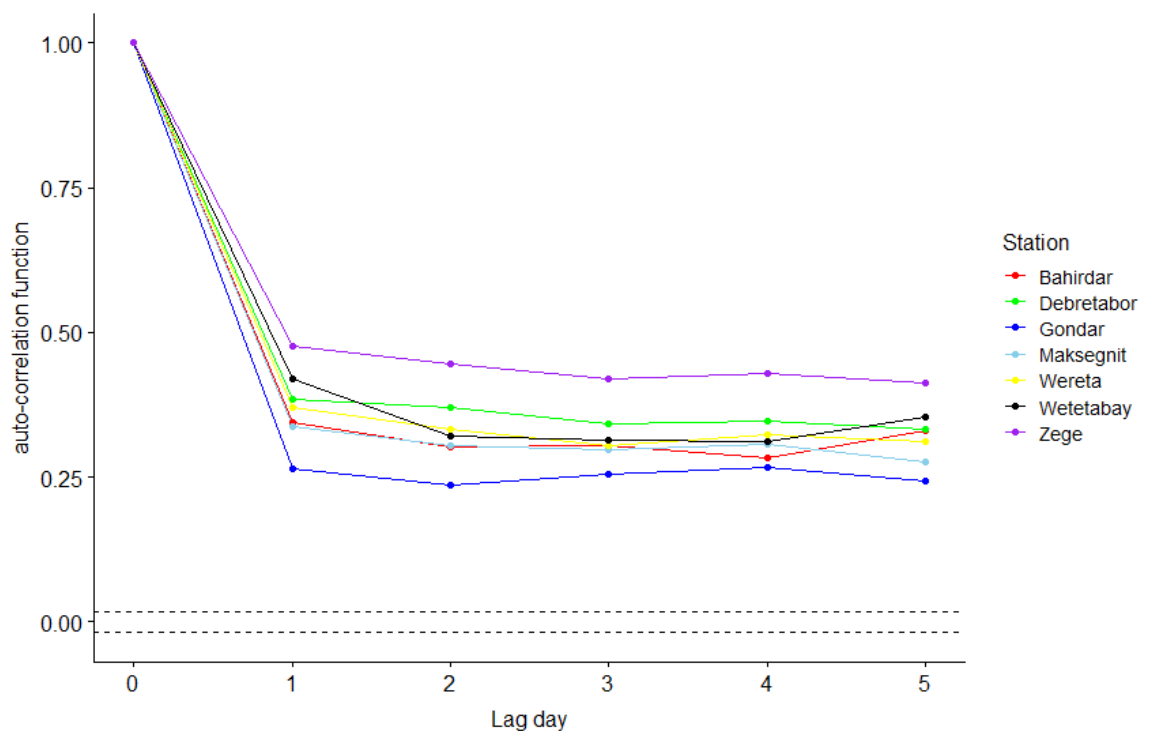


Figure 2-3: Autocorrelation of daily rainfall at main stations in the study area (the dashed lines represent the upper and lower limits of significance level at 95% confidence interval calculated based on equation 2).

### 2.3.1.2. Spatial and temporal variation of rainfall

Time series rainfall plots were also analysed to see the long-term pattern and variability. There are intra- and inter- daily, monthly, seasonal and annual variability of rainfall of the stations considered in this study. On the one hand, the rainfall patterns are relatively consistent during the dry months (January, February, November and December) when compared to March, April and May. On the other hand, wet months (June, July, August, and September) are highly variable. The rainfall records of each station either showed a downward or an upward trend. But, the p-values of Mann-Kendall and seasonal Mann-Kendall tests were greater than 0.05 for most rainfall stations considered in this study indicating that the changes were statistically not significant. While most of the stations showed similar trend direction in both seasons, the direction of trends are opposite in the rainy and the dry season in some stations (Table 1). Mean areal basin rainfall of recent years records are showing a negative deviation from the normal average values (Fig. 4A) and a few stations like Bahir Dar (Fig. 4 C), Amed Ber, Adet, Addis Zemen, Enfranz, Maksegnit and Wetetabay show a downward trend on daily, seasonal and annual rainfall even though the change is statistically not significant. To the contrary, Dangila, Debre Tabor, Merawi, Tis Abay and Wereta are showing upward trends with p-values greater than 0.05, so that no significant trend could be detected (null hypothesis). The geographic locations of the stations are shown in Fig. 5. The annual rainfall change is mostly insignificant except for Enjibara, Gondar and Zege stations that show a significant upward trend and Addis Zemen downward trend. Nevertheless, there are a few more stations that showed a significant change in seasonal rainfall (Table 1). Gebremicael et al. (2013) also reported an increasing trend for Gondar station but with insignificant change. The significant increase (decrease) of seasonal rainfall are related to the timing (late onset and early cessation) and very short duration



rainfall events (Teshome 2016). Moreover, variations of the north-south movement of ITCZ and the El Niño teleconnection that affects the sea surface temperatures (SSTs) of the Indian and Atlantic oceans are the most probable factors that cause seasonal variability of the rainfall in the study area (Gleixner et al. 2017). Around 50% of the Ethiopian summer rainfall variances are influenced by equatorial Pacific SST variability (Gleixner et al. 2017).

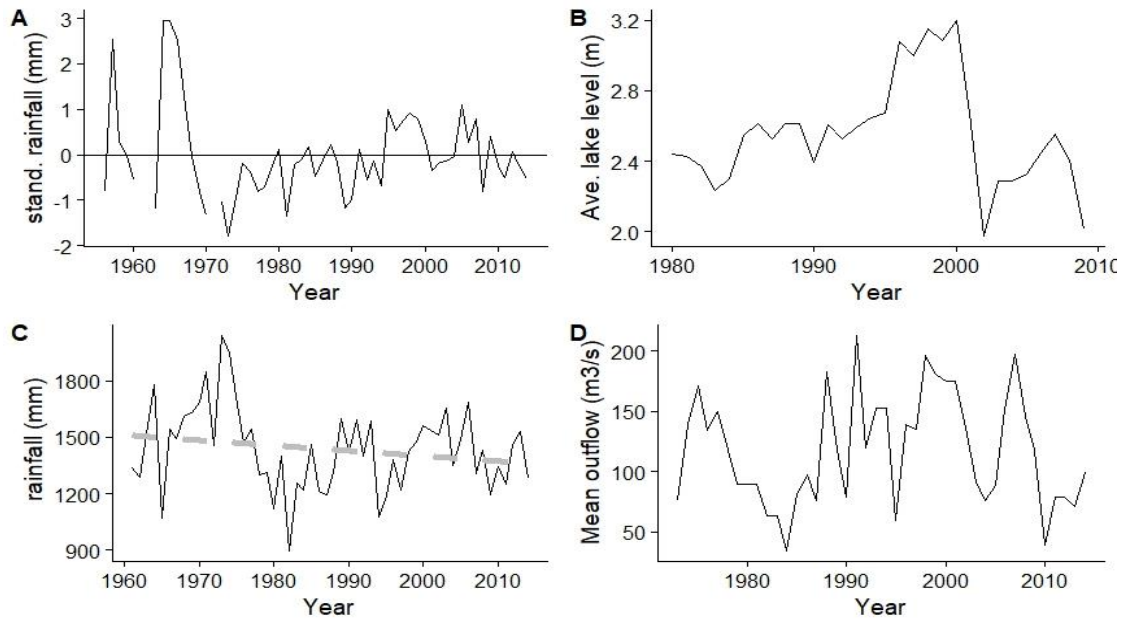


Figure 2-4: Annual plots of standardized rainfall of Lake Tana Basin (A), mean of the Lake Tana water level (B), long-term series trend of Bahir Dar station (C), and long-term behaviour of mean outflow from the Lake (D).

**Spatial variation of rainfall:** There is significant variation of the annual rainfall distribution in the basin. An annual rainfall map has been produced based on the long-term mean annual rainfall records by applying inverse distance weighted interpolation (IDW) in a GIS environment (Fig. 5). The map shows a general N-S gradient of rainfall. The south western part of the basin has the highest rainfall and northern and north western part receives less rainfall (Fig. 5). The minimum, maximum and mean annual rainfall values are 815, 1599, and 1238 mm respectively. The standard deviation value is 160 mm.

Table 2-1: Trend test results of MK and seasonal MK for daily, seasonal and annual rainfall data for selected stations in the study area (\*\*\*, \*\*, and \* represent significant change at  $\alpha = 0.001, 0.01, \text{ and } 0.05$ , plus and minus signs indicate upward & downward trends respectively)

Station	Daily		Seasonal		Annual	
	$\tau$	p-value	$\tau$ / p-value rainy season	$\tau$ / p-value dry season	$\tau$	p-value
Adet	+	0.60	- / 0.06	+ / 0.56	-	0.05
Addis Zemen	-	***	- / ***	+ / 0.56	-	*
Amed Ber	-	0.36	- / ***	- / ***	-	0.05
Bahir Dar	-	***	- / 0.60	+ / 0.12	-	0.46
Dangila	+	0.34	+ / 0.31	+ / 0.78	+	0.13
Debre Tabor	+	***	- / 0.34	+ / 0.75	+	0.93
Delgi	-	0.10	- / 0.24	- / 0.11	-	1.00
Dera Hamusit	+	0.20	+ / 0.85	- / 0.90	-	0.15
Enfiranz	-	0.16	- / 0.27	+ / 0.86	-	0.14
Enjibara	+	***	+ / ***	+ / 0.85	+	*
Gondar	+	***	+ / 0.84	- / 0.16	+	**
Maksegnit	+	*	+ / 0.21	+ / 0.51	+	0.88
Mekaneyesus	+	**	+ / **	+ / ***	+	0.62
Merawi	+	0.87	+ / ***	- / *	+	0.85
Tis Abay	+	0.23	+ / **	+ / 0.79	+	0.20
Wereta	+	0.30	+ / ***	+ / 0.75	+	0.61
Wete Abay	-	0.33	+ / 0.58	- / 0.53	-	0.37
Zege	+	0.75	+ / ***	- / *	+	*

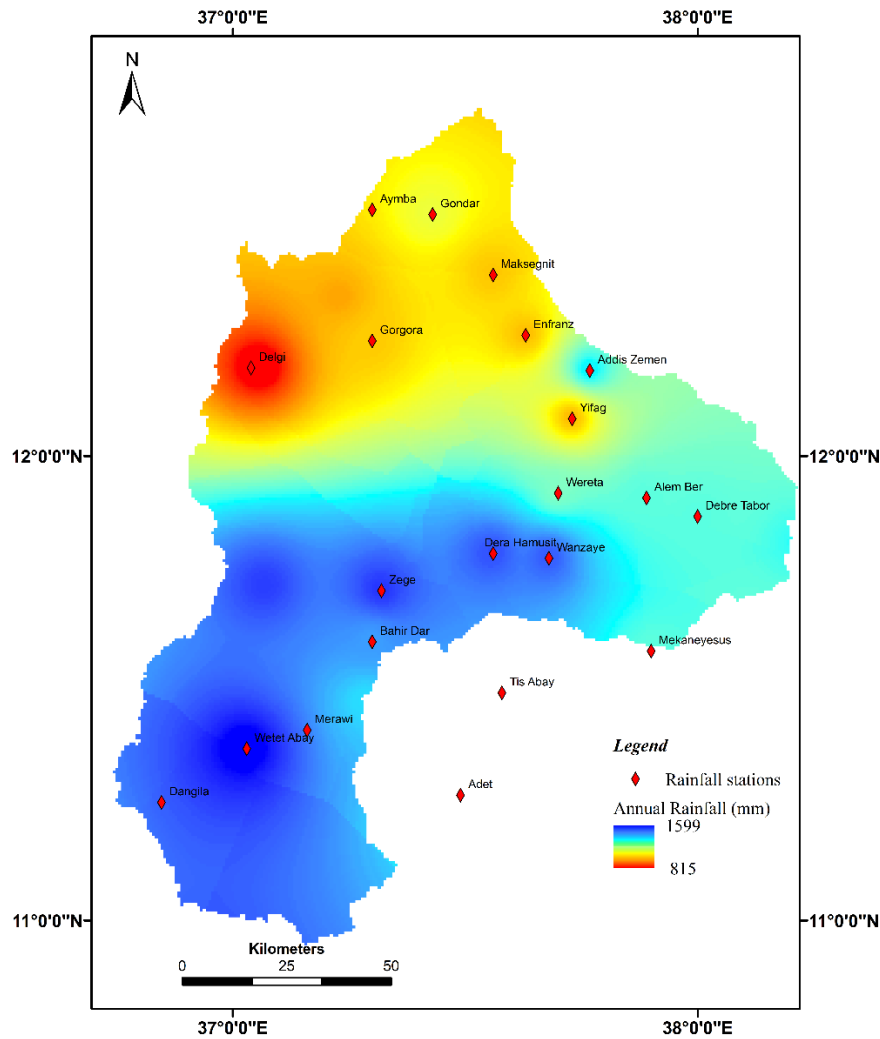


Figure 2-5: Annual Rainfall distribution of Lake Tana Basin produced using long-term mean values of rainfall records at each station.

### 2.3.2. Stream flow analysis

About 93% of the water of the Lake Tana originated from only four major rivers: Gilgelabay, Ribb, Gumara and Megech. Among the four contributors, Gilgelabay is the largest one with a long year daily average discharge of  $55 \text{ m}^3/\text{s}$  and Gumara is the second largest contributor with an average flow of  $34 \text{ m}^3/\text{s}$ . Ribb contributes a mean flow of  $14.4 \text{ m}^3/\text{s}$  and Megech is the least contributor ( $9 \text{ m}^3/\text{s}$ ) among the four tributaries considered in this study (Fig. 6). The analysis shows that outflow from the lake is decreasing particularly between the years 2002-2006 and 2008-2011 (Fig. 4D). Possible reasons that might contribute to the abrupt change of the outflow are linked to anthropogenic activities. Intensive development interventions are taking place at

the major tributary rivers. Damming and abstraction of water is taking place since recent years (Alemayehu et al. 2010; Minale and Rao 2011; Abate et al. 2015). These activities are influencing the water level of Lake Tana. In addition to the human induced factors, natural changes on the rainfall amount and intensity in the catchment are considered to be one of the main reasons for decreasing outflow.

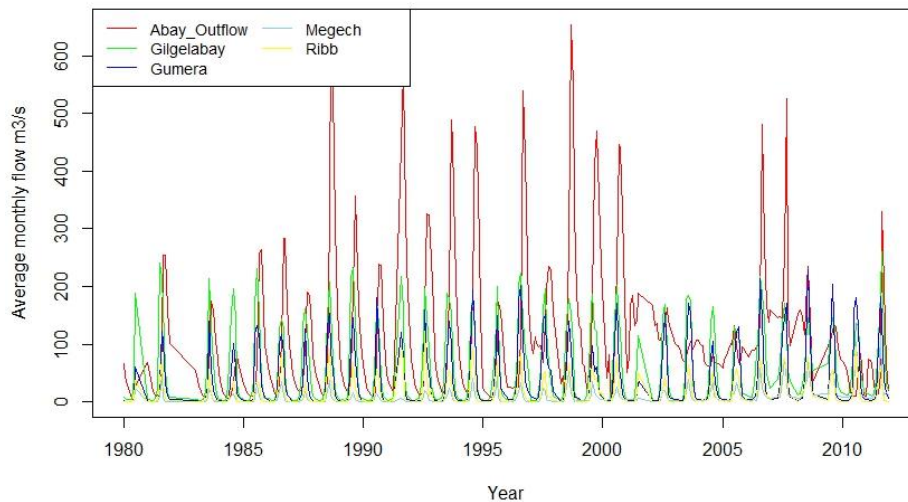


Figure 2-6: Time series plots of average monthly streamflows of main tributary rivers and outflow ( $\text{m}^3/\text{s}$ ) of Lake Tana.

The streamflow changes were detected on a daily and annual basis as well as in the wet and dry seasons (Fig. 7). All stations show a significant increase on the daily time scale (Table 2). However, Gumara and Megech were the only stations that showed a significant upward change at annual and seasonal time scales, as well (Table 2). The lake water level showed a significant increase during the wet season and a significant decrease during the dry season, resulting in no significant annual trend. Gilgelabay showed a decreasing trend in the wet season, but no significant trend was detected for the dry season and on the annual time scale. The outflow from the lake and Ribb station have opposite changes in the wet and dry season, but these changes are not significant (Table 2).

Table 2-2: Trend test results of MK and seasonal MK of the daily, seasonal and annual outflow and inflow discharges at the gauging stations (\*\*\*, \*\*, and \* represent significant

change at  $\alpha = 0.001, 0.01$  &  $0.05$  respectively, plus and minus signs of  $\tau$  indicate upward & downward trends respectively).

Station	Streamflow trends on					
	Daily		Seasonal		Annual	
	$\tau$	p-value	Wet season ( $\tau$ /p-value)	Dry season ( $\tau$ /p-value)	$\tau$	p-value
Abay/outflow	+	***	- / 0.41	+ / 0.52	+	0.95
Gilgelabay	+	***	- / *	+ / 1.00	-	0.74
Gumara	+	***	+ / **	+ / ***	+	***
Megech	+	***	+ / ***	+ / ***	+	***
Ribb	+	***	+ / 0.81	- / 0.31	+	0.57
Lake water level	+	***	+ / ***	- / ***	+	0.57

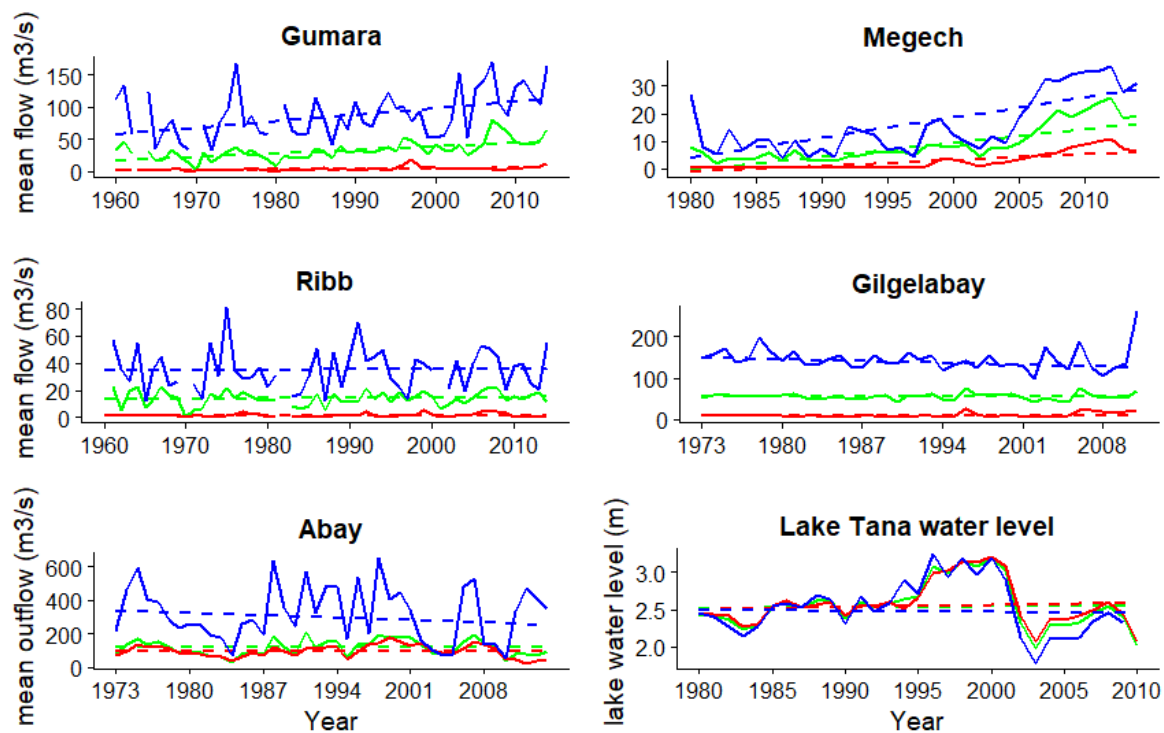


Figure 2-7: Long term trends of annual (green), wet season (blue) and dry season (red) of mean streamflows, outflow ( $\text{m}^3/\text{s}$ ) and water level of Lake Tana. Solid and dashed lines represent time series and trend lines respectively

Based on the Tukey's multiple mean comparison test, the decadal means of the outflow between the 1980s and the 1990s show a significant increase ( $p\text{-value} = 0.03801$ ), to the contrary a significant decrease was observed between the 1990s & the 2010s ( $p\text{-value} = 0.02316$ ). Thus, there was sufficient evidence (at  $\alpha \text{ level} = 0.05$ ) to conclude that the means of decades 1980s and 1990s, and 1990s and 2010s were significantly different. On the other hand,

this test indicates that there were no significant variations of the decadal means between the 1970s and the 1980s, the 1970s and the 1990s, the 1970s and the 2000s, the 1980s and the 2000s and the 1990s and 2000s. The inter-annual variability of the outflow increases from 34% (case of 1990s) to 40% (case of 2000s). These test results are in agreement with a previous study of Conway and Hulme (1993) but are contrary to the findings of Gebremicael et al (2013) and Tesema et al. (2010). Gebremicael et al (2013) reported that annual streamflow of Upper Blue Nile Basin showed a significant increase from 1971 to 2009. Tesema et al. (2010) also found a significant increase of the outflow of Lake Tana over the period from 1959 to 2003. Our investigation showed a disagreement with the above two results as our analyses were carried out on the basis of a ten years moving average while the other studies were focused on one long time period. Additionally, the mean seasonal outflow values changed downward in wet season and upward during the dry season, but these changes were not significant ( $p$ -values=0.41/0.95). Similar tests were done for inflow discharges into the lake. The Megech and Gumara flows showed statistically significant variation of the mean values at  $\alpha$  level=0.05. Annual mean flow of Gumara for the 2000s and the 2010s are significantly increasing compared to the 1960s ( $p$ -value=0.014 and 0.001), the 1970s ( $p$ -value=0.0013 and 0.004) and the 1980s ( $p$ -value=0.003 and 0.008) (Fig.7). The mean flows for other decades do not show a significant change. The result shows agreement with a similar study conducted for the whole Abay/Blue Nile basin 2013 (Gebremicael et al. 2013; Tekleab et al. 2013). The decadal mean annual flow of Megech for the 2000s showed a highly significant ( $p$ -values< 0.001) increase when it is compared with the 1980s and 1990s. On the other hand, Gilgelabay and Ribb flows were not showing a significant variation of their decadal means. Gilgelabay flow has shown an increase in the mean from 1980s to 1990s and again a decrease from 1990s to 2000s but it is not statistically significant ( $p$ -value>0.05). The intra-annual variability of Gilgelabay

streamflow increases by 9%, 17% and 25% during 1980s, 1990s and 2000s, respectively (Figure 8).

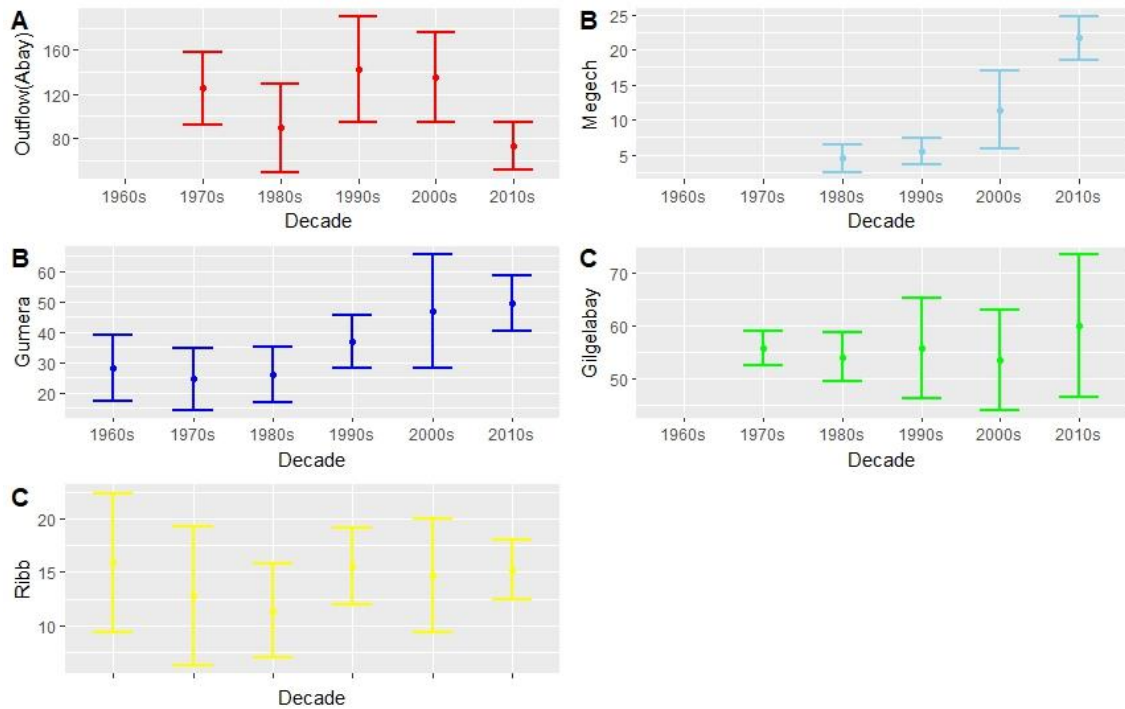


Figure 2-8: Decadal variability of annual mean streamflow of major rivers: ‘A’ shows a significant decrease in recent decade for the outflow record, group ‘B’ shows a significant increase from decade to decade for Megech & Gumera and group ‘C’ shows slight but not significant change for Gilgelabay & Ribb.

The high degree of variabilities of streamflow and the change of runoff magnitude in the study area are mainly caused by the combined effect of land use dynamics and changes on the rainfall intensity and duration. For instance cultivation land of the Eastern Lake Tana Basin was increased by 72.7% while the forest cover was decreased by 71.3% and the degraded land was increased by 31.34% between the years 1985 and 2011 (Gashaw & Fentahun, 2014). Woldesenbet et al. (2017) reported that continuous expansion of cultivated land and decline in woody shrubs and natural forest were the major changes of Lake Tana Basin in the period from 1973 to 2010. In addition to land use changes, recently the number of rainy days in a year are decreasing while total rainfall remains more or less constant with high intensity (Teshome 2016). These are important factors causing high runoff magnitudes by decreasing the rate of infiltration.

#### 2.3.2.1. Discharge autocorrelation analysis at different time lags

Based on our analyses, the daily streamflow is a non-random process that shows high seasonal variability. The autocorrelation coefficients of each river have a maximum value at lag one day and steeply decrease as the lag time is increased. Arora et al. (2014) found similar result for a glacier catchment in the Himalayas. As Fig. 9 indicates, the maximum autocorrelation coefficient values are at lag 1 for each of the rivers. Abay discharge which is the outflow from the lake has the highest lag 1 autocorrelation coefficient (0.99). The autocorrelogram of the outflow has the highest of all. This shows that the lake outflow strongly depends on the previous day outflow as it is a function of the lake water level. Megech discharge has the lowest lag 1 autocorrelation (0.56) due to a large variation during a few months of high flows. All of the rivers have similar characteristics with respect to autocorrelations that show maximum autocorrelation with the previous day's discharge ( $Q_{i-1}$ ) indicating storage effects of the previous day streamflow. Consequently, it is easier to forecast the streamflow of the next day if the discharge of the previous day is known. All plots except Megech's start with a high autocorrelation at lag 1 and generally decrease linearly with little noise. Such a pattern is assumed to be a signature of "strong autocorrelation", which in turn provides high predictability. Megech's discharge autocorrelation plot has a different shape due to the high variability of the data series from decade to decade. It has moderately high autocorrelation at lag 1 (value=0.56) and gradually decreases for longer lag times. The decreasing autocorrelation is generally linear with some noise which indicates that the pattern is moderately autocorrelated. In summary, results of the autocorrelation tests are significantly different from zero so that our null hypothesis (independency and randomness of the streamflow data) was rejected and the alternative assumption (events of the daily streamflow time series were dependent to their preceding events at time lag-k) was accepted (Matalas 1967; Modarres et al. 2007; Gautam et al. 2010; Duvert et al. 2015).



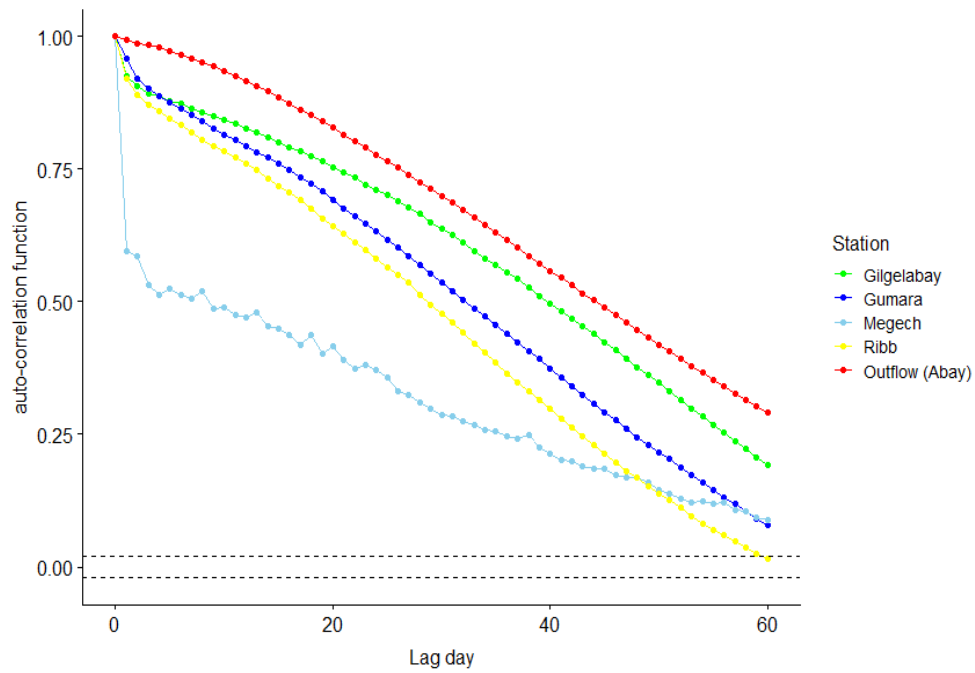


Figure 2-9: Autocorrelation of daily discharges until at a lag time of 60 days (the dashed lines represent the upper and lower limits of significance level at 95% confidence interval calculated based on equation 2)

#### 2.3.2.2. Discharge cross-correlation analysis at different time lags

Most of the time, surfaces runoff generation is not taking place during the rainfall events as there may be initial soil moisture deficit that should be satisfied during the beginning of the rainfall events (Wagner et al. 2016). Moreover, the soil, land use and land cover conditions of catchments affect runoff generation. There are clear differences among cross-correlation (cc) coefficients of rainfall and streamflow in the Lake Tana Basin (Fig. 10). Thus, the cc values show strong correlation after one month time lag. Gumara has the highest cc value (0.68) after a time lag of 31 days, Gilgelabay, Ribb and Megech have their maximum cc values of 0.65, 0.62 and 0.42 after 35, 20, and 32 days lag, respectively. These positive correlation coefficients between rainfall and streamflow with lagging time are a signature of an autoregressive model (Osman et al. 2017). On the other hand, the outflow discharge cross-correlation behaviour is different from the other four due to large storage capacity of the lake and its maximum cc value is achieved after more than 60 days. The cross-correlation coefficient between daily rainfall and streamflow at other time lags are comparatively small even though all values are

statistically significant at 95% confidence interval. The outflow discharge (Abay) from the lake has different correlation behaviour with rainfall indicating that its response is not only dependent on rainfall but also depends on other inputs such as inflow discharges into the lake. For example, the lake storage has a retarding effect on the peak flow of Abay (Setegn et al. 2008). In conclusion, the daily streamflow and catchment rainfall time series are correlated and the correlation coefficients at time lag  $k$  between daily streamflow and rainfall were statistically significantly different from zero. This result showed an agreement with our alternative assumptions.

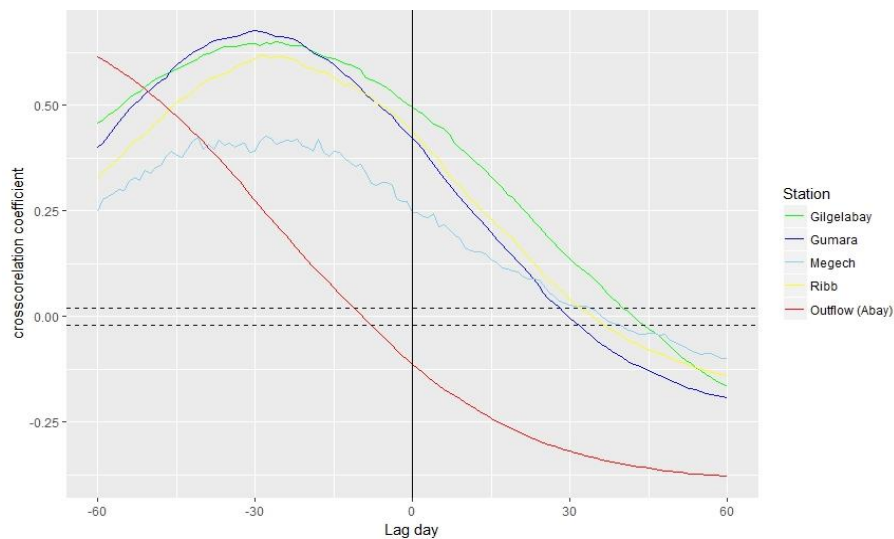


Figure 2-10: Cross-correlation between river discharge and regional rainfall of sub-basins in Lake Tana Basin. The correlograms are generated by cross-correlating flows of Gilgleabay, Gumara, Megech, Ribb and outflow from the Lake (Abay) with their corresponding regional rainfall

### 2.3.3. Lake water level analysis

The Lake level varies seasonally. Its maximum level is recorded in September which is one month after the peak rainfall (Fig.11). There is an inter-annual variability of the water level (Fig. 4B). The mean lake water level for the 1980s was 2.47 m and it increased to 2.77 m in the 1990s and declined again to 2.42 m in the 2000s. Moreover, the dry season water level showed a significant decrease over time ( $p$ -value  $< 0.001$ , Table 2). To the contrary, the wet season showed a significant increase ( $p$ -value  $< 0.01$ , Table 2). The lake water level showed

an abrupt decline during 2002 (Fig.4B). The sharp drop of the lake level was caused as a result of an attempt to maximize electricity production by regulating the lake outflow after the construction of Chara Chara weir from the end of 2001 at Tis Abay (Setegn et al. 2008; Alemayehu et al. 2009; Rientjes et al. 2011). The extended crop production by farmers since 2003 on about 562 ha of the Lake Tana bed following the lower lake levels was a good example of the annual impact which made the lake level unable to restore to its level previous to 2002 (Alemayehu et al. 2009, Minale & Rao 2011). This indicates that lower water levels during dry season will almost certainly result in people moving both cultivation and grazing onto the dried lake bed. Moreover, this would exacerbate adverse impacts on near-shore vegetation and could greatly increase sedimentation in the lake (Alemayehu et al. 2009).

Similar to the outflow discharge the decadal mean of the lake water level significantly decreases from 1980s to 1990s and 1990s to 2000s. The difference of the lake water level between the 1980s to 1990s was about 0.30 m. On the other hand the level dropped by 0.35 m between the 1990s to the 2000s. These changes were consistent with outflow discharge at Bahir Dar gauging station. The coefficient of variation increased in all of the three decades, underlining the variability of the Lake Tana level in the stated periods.

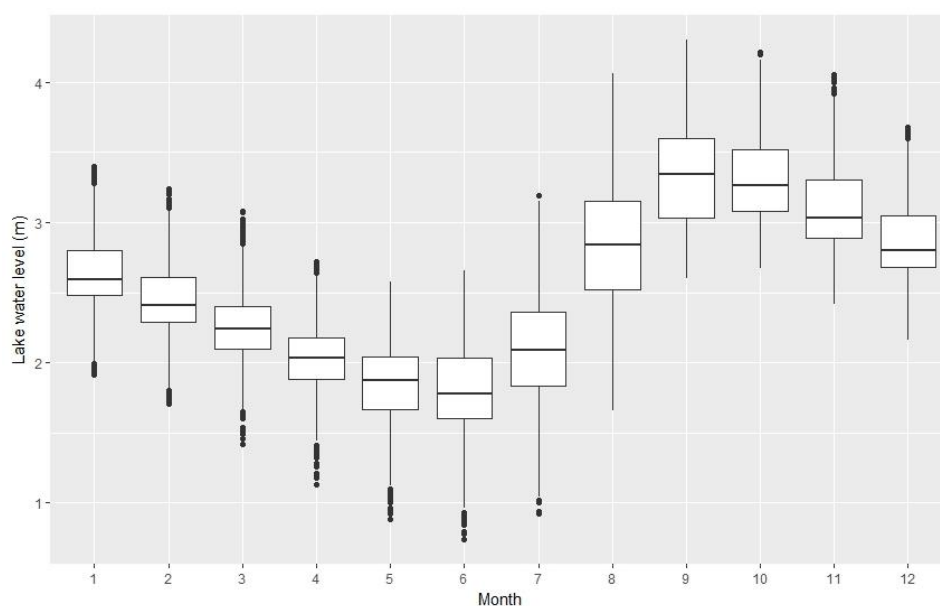


Figure 2-11: Boxplot showing seasonal variability of the Lake Tana water level.

## 2.4. Conclusions

In this study, rainfall, lake level and streamflow data of several years were analysed. The rainfall pattern in the basin is monomodal with a peak in July or August. The direction of Mann-Kendall trend test vary among annual, dry and wet seasons as well as daily rainfall and streamflows implying that the time period of investigation matters. The annual rainfall change over time is mostly not statistically significant. About 55% of the rainfall stations showed a positive trend and only three of them (Enjibara & Zege at  $\alpha = 0.05$ , Gondar  $\alpha = 0.01$ ) showed significant changes. The remaining 45% of the station showed insignificant downward trends except Addis Zemen. But the seasonal changes were significant for eight stations (Table 1). The summer rainfall changes could be related to SST variation. The maximum lake water level is recorded in the month of September, following the maximum amount of rainfall in the previous months. The annual mean lake water level has shown a decreasing trend from decade to decade and since the year 2002. The long-term annual mean lake water level is about 2.6 m. The autocorrelation coefficient values of daily rainfall and streamflow are decreasing linearly as the time lag increases but they are significantly different from zero indicating that the data come from an underlying autoregressive process with moderate to strong positive autocorrelation (Matalas 1967; Modarres 2007; Gautam et al. 2010) . The streamflow values have their maximum cross-correlation coefficient after 20- 60 days due to basin lag time caused by the shape of the catchment, size of the drainage basin, soil and vegetation cover.

In general the Lake Tana Basin is a hydrologically highly dynamic area that shows high variability on the daily, monthly and yearly streamflow and the lake water level. The changes in streamflow and the lake water level are mainly linked to intensive land use changes such as expansion of intensive agriculture, urbanization and deforestation as well as change in the number of rainfall days and intensity. Improvements in agricultural water management could help to increase the water use efficiency, which consequently may contribute to mitigate the

decreasing trends.

### **3. Modeling the impact of agricultural crops on the spatial and seasonal variability of water balance components in the Lake Tana Basin, Ethiopia**

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## **Abstract**

The Lake Tana basin hosts more than 3 million people and it is well known for its water resource potential by the Ethiopian government. The major economic activity in the region is agriculture, but the effect of agricultural crops on water resources is poorly understood. Understanding the crop water interaction is important to design proper water management plans. Therefore, the primary objective of this research is to investigate the effect of different agricultural crops on the spatial and seasonal variability of water balance components of Gilgelabay, Gumara, and Ribb catchment areas of Lake Tana Basin, Ethiopia. To this end, the hydrologic model SWAT was used to simulate the water fluxes between 1980 and 2014. The water balance components, which were mapped for each hydrologic response unit, indicated the spatial variations of water fluxes in the study. Cereal crops like teff and millet had significant effect in enhancing groundwater recharge, whereas leguminous crops like peas had significant impact in increasing runoff generation. Moreover, the model outputs showed that the total streamflow is dominated by baseflow and about 13%, 9%, and 7% of the annual rainfall goes to the deep aquifer system of Gilgelabay, Gumara, and Ribb catchment areas, respectively.

**Keywords:** groundwater recharge; land use land cover; SWAT; Lake Tana

### **3.1. Introduction**

Agriculture, food production and water are inseparably linked (Watts et al. 2015). Water use in agriculture accounts for 70% of the global total water use (Hatfield 2014). Consequently, it has a significant impact on the water balance components. Agricultural land use affects the hydrologic cycle in terms of the partitioning of rainfall between evapotranspiration, runoff, and groundwater recharge (Watts et al. 2015). The quality of surface water and groundwater has generally declined in recent decades mainly due to an increase of agricultural and industrial activities (Parris 2011). The complete drying up of Haramaya Lake in Eastern Ethiopia since 2005 is an example for the consequences of decreasing groundwater levels due to over-pumping for agriculture and household use (Abebe et al. 2014). To prepare for the future and avoid past mistakes, modeling the effect of agricultural crops on the spatial and seasonal variation of water balance components is required. Although several water balance studies have been performed globally, only a few of them focused on the effect of agricultural crops on water balance components. For example, Zhao et al. (2010), studied the effect of vegetation change and climate variability on streamflow of seven paired catchments in Australia, New Zealand, and South Africa. Li et al. 2019 also studied the spatio-temporal impacts of land use and land cover changes on the hydrology of the Wei River Basin, China.

The agriculture sector plays a central role in the Ethiopian economy, where about 85% of all employment relies on it (FAO, 2014). This economic sector is dominated by small-scale farmers who depend on rain-fed mixed farming. Crop production accounts for about 60% of the agricultural outputs (Gebre-Selasie and Bekele 2012). The crop productivity varies with the availability of water and water use in agriculture. Although Ethiopia is perceived as the water tower of Eastern Africa, temporal variability (seasonality) and uneven spatial distribution of water resources remain the primary challenge. Availability of water is highly dependent on the seasonality and inter-annual variability of rainfall and streamflow. The temporal variabilities



of rainfall and streamflow extremes are linked to low frequency climate processes centred over the mid-latitudes of the Pacific basin (Taye et al. 2015). These temporal variabilities are manifested in widespread, devastating droughts and floods (World Bank 2006). Thus, agricultural crop yields are frequently affected by the quantity and timing of rainfall. To overcome this widespread problem, understanding the effect of agricultural crops on the hydrologic cycle is important.

Due to the complex physical processes of the hydrologic cycle, direct measurement of the water balance components such as groundwater recharge, evapotranspiration, and surface runoff on a spatial basis is difficult. Therefore, process-based distributed parameter models are needed to simulate the spatial and temporal patterns of hydrologic response (Jiang et al. 2007). Among others, the semi-distributed SWAT hydrologic model (Arnold et al. 1998) is suitable to determine recharge rate, evapotranspiration, and runoff on various spatial and temporal scales (Gemitzi et al. 2017).

Because of its national and international importance, the Lake Tana Basin became a focus area of many scientific studies under different perspectives. These include water balance analyses of different sub-catchments including the lake (Derib 2013; Tegegne et al. 2013; Dessie et al. 2015), hydrological modeling with emphasis on surface water (eg. Dessie et al. 2014; Worqlul et al. 2015; Polanco et al. 2017), hydrometeorological trend analyses (e.g. Gebrehiwot et al. 2014; Mengistu and Lal 2014; Tigabu et al. 2018), climate change impact studies (e.g. Koch and Cherie 2013; Teshome 2016), land use/cover change impact on hydrologic responses (e.g. Gumindoga et al. 2014; Wollesenbet et al. 2017), implications of water harvesting intensification on upstream–downstream ecosystem services and water availability (e.g. Dile et al. 2016), and groundwater and hydrogeology (e.g. Yitbarek et al. 2012; Awange et al. 2014).

Most of the hydrological studies in the Lake Tana basin focus on water balance evaluations at catchment outlets and lack detailed mapping of water balance components on a spatial basis. Another important research gap is that the hydrologic studies do not investigate the hydrologic mass balance in relation to vegetation types (van Griensven et al. 2012). Although the SWAT model was used to investigate the effect of land use change on the hydrology of the basin, none of the papers explicitly addressed the crop-related effects on the water fluxes. Hence, the overarching goal of this research is to analyze how the hydrologic mass balances are affected by agricultural crops and soil types. In particular, we focus on the spatial and seasonal distribution of groundwater recharge, surface runoff, and actual evapotranspiration (ET) in the Gilgelabay, Gumara, and Ribb catchments, Lake Tana Basin, Ethiopia. To the best of our knowledge, this is the first attempt to (i) analyse the impact of agricultural crops on the hydrologic cycle and to (ii) map major water balance components in the Lake Tana Basin in detail.

### **3.2. Materials and methods**

#### **3.2.1. Study area**

The Lake Tana basin is located in the north-western highlands of Ethiopia. It is the second largest sub-basin of the Blue Nile River. Lake Tana is the largest freshwater lake in Ethiopia and the third largest in the Nile Basin (*Figure 3-1*). The catchment area of the lake at its outlet is 15,321 km<sup>2</sup>. About 20% of the catchment area is covered by Lake Tana (Alemayehu et al. 2010). The catchment is approximately 84 km long and 66 km wide. The lake has a surface area of 3,156 km<sup>2</sup>. Lake Tana is the source of the Blue Nile River. It contains about 50% of the country's fresh water (Costa et al. 2014). More than 40 rivers and streams flow into Lake Tana with a mean annual inflow of 158 m<sup>3</sup>/s (Alemayehu et al. 2010), but 86% of the water originates from three major rivers: Gilgelabay, Gumara, and Ribb (Setegn et al. 2008, Alemayehu et al. 2010). The only surface outflow from the lake is the Blue Nile (locally referred to as Abay)

River with an annual flow volume of 4 billion m<sup>3</sup> (127 m<sup>3</sup>/s) measured at the lake outlet (Setegn et al. 2008).

The spatial and temporal variation of rainfall in the basin is determined by elevation and the movement of the inter-tropical convergence zone (ITCZ). The position of the ITCZ is the most dominant factor that controls the amount of summer rainfall in the basin. In the Lake Tana Basin, rainfall has a high seasonal variability: July, August, and September are wet months with the highest amounts of rainfall when the ITCZ position is in the northern hemisphere, June and October are transition months between wet and dry seasons, November through March belong to the dry season, and April and May are months with small rainfall amounts. There is also high spatial variability of annual, seasonal, and monthly rainfall amounts in the study area because of small changes in the location of the ITCZ (Woldesenbet et al. 2017). Additionally, topography has a pronounced impact on rainfall amounts in the region. The topography varies significantly from lowland flood plain (1700 m) to high mountain ranges (4400 m). This variation leads to annual rainfall variability and occurrence of different climatic zones within the basin (Melesse et al. 2011). The amount of annual rainfall is directly related to elevation above mean sea level: high rainfall is observed in the highlands, whereas low rainfall is measured in the lowlands (Tigabu et al. 2018). Moreover, large (global) atmospheric circulation and sea surface temperatures such as large scale forcing through El Niño Southern Oscillation (ENSO), Quasi-Biennial Oscillation (QBO), as well as west-east sea surface temperature gradients over the equatorial Indian Ocean are significantly influencing rainfall variability (Awange et al. 2014).

### 3.2.2. Data base

Daily rainfall and minimum and maximum temperature values from 5 meteorological stations for the years 1980 to 2014 were used, which were provided by the National Meteorological Service Agency (NMA 2016). Daily streamflow data of Gilgelabay near Merawi, Gumara near

Bahirdar, and Ribb near Addis Zemen gauging stations for the years 1980 to 2014 were obtained from the Department of Hydrology, Ministry of Water, Irrigation and Electricity of the Ethiopian Government (MoWIE 2016).

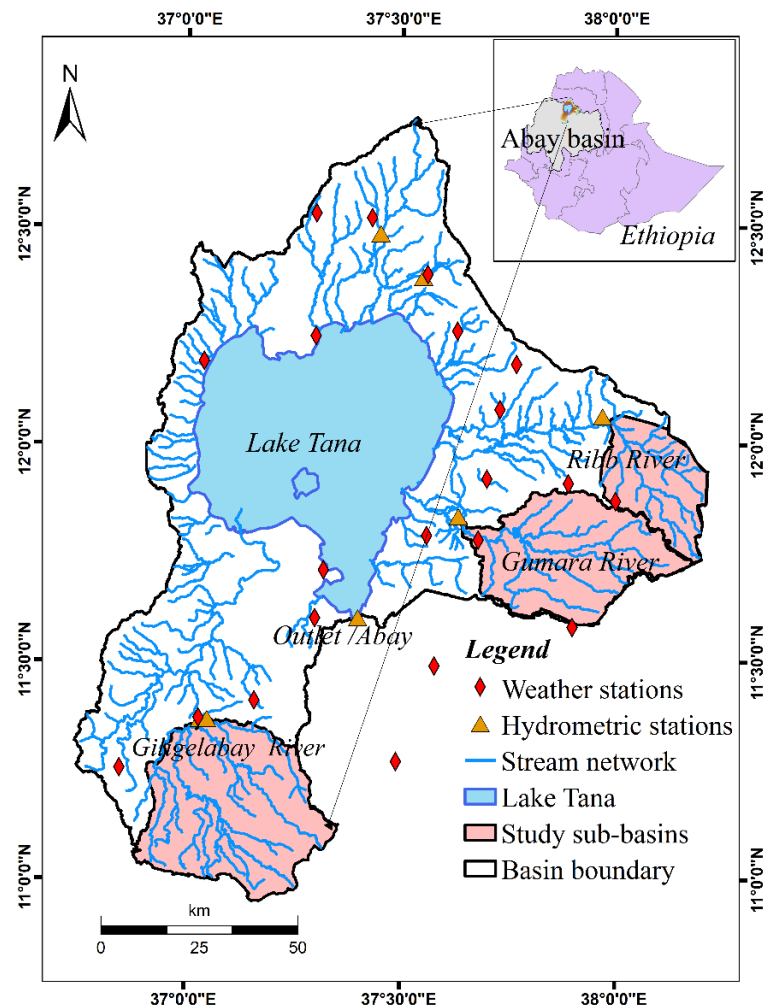


Figure 3-1: Location map and major tributaries of Lake Tana including river gauging and weather stations

Land use and land cover as well as soil data at a scale of 1:50000 were provided by the Amhara Design & Supervision Works Enterprise (ADSWE 2017). About 60.2% of the basin is covered by agricultural land. This area is further classified as intensively cultivated (37.3%), moderately cultivated (16.0%), and farm villages (6.9%) (Figure 3-2). The soils in the study area are highly heterogeneous. Eutric Leptosols are covering around 50% of the total area followed by Eutric Nitosols (13%). The soil textural classes vary from sandy-loam to clay (Eutric Regosols

grouped to sandy-loam, Eutric Fluvisols and Eutric Leptosol to loam, Chromic Luvisols and Haplic Nitosols to clay-loam, and Haplic Alisols to clay). Infiltration rates vary from moderate (hydrologic soil group B: Eutric-Leptosols and Regosols), to slow (hydrologic soil group C: Chromic Luvisols, Eutric Fluvisols), to very slow (hydrologic soil group D: Eutric Vertisol, Haplic Alisols, Haplic Nitosols). The Shuttle Radar Topography Mission (SRTM) global digital elevation model (DEM) data with a 30 m by 30 m resolution was used as topography input data (USGS 2016).

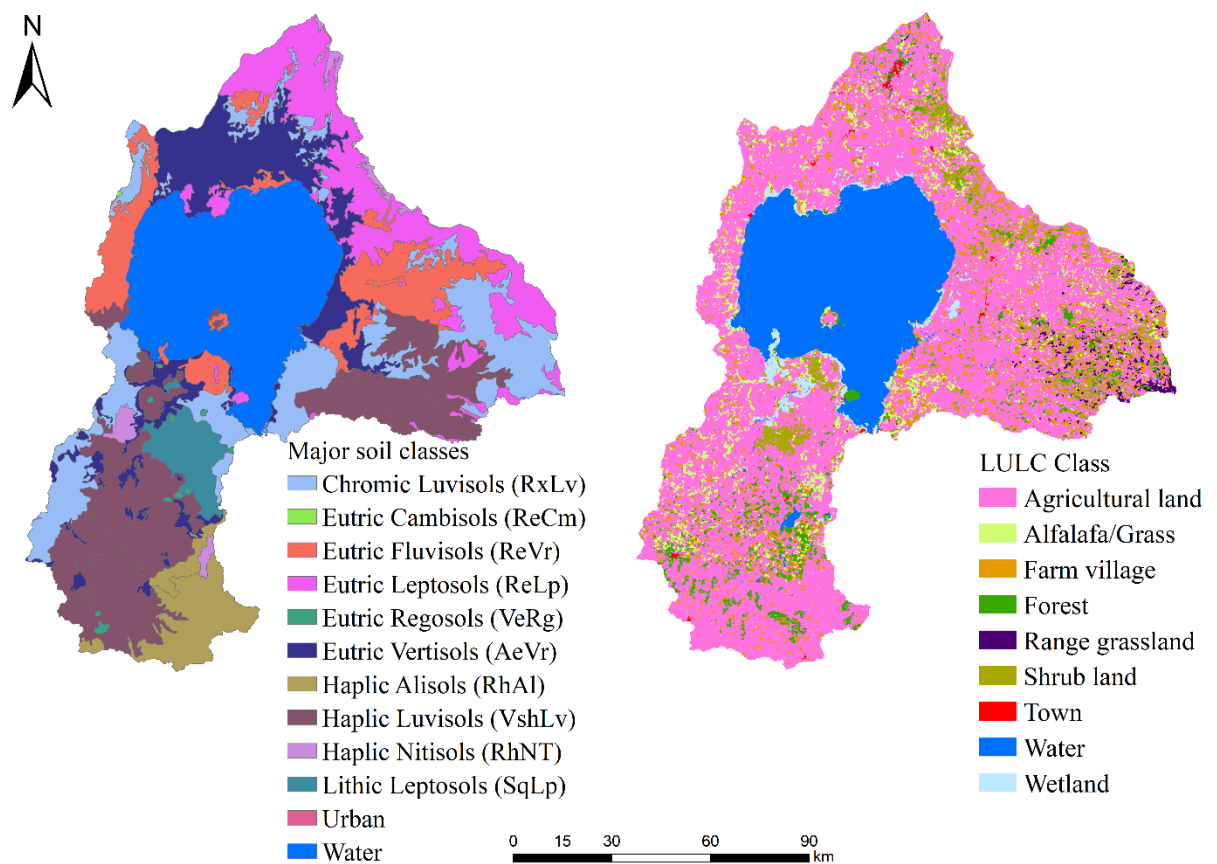


Figure 3-2: Spatial distribution of major soil units (left) and land use land cover (LULC) (agricultural land, alfalfa, shrub land, forest, grassland, water body, and wetland) of the Lake Tana Basin

### 3.2.3. Hydrologic modeling

To achieve the research goal of the current study, the semi-distributed, continuous eco-hydrologic model SWAT (Soil and Water Assessment Tool) (Arnold et al. 1998; Arnold and

Fohrer 2005) was used. The model is capable of simulating spatially distributed water balance components based on hydrological response units (HRUs). Four main steps comprise the modeling approach:

1) Hydrological model setup: Three independent SWAT models were setup for the three catchments Gilgelabay, Gumara, and Ribb based on available climate, land use, soil, and digital elevation model data. No water withdrawal was considered in the model setup as this information was not available. The three independent model setups were used to better represent each catchment, e.g. by a more precise representation of the stream network. In this study, the SWAT model was not setup for the entire Lake Tana basin. Although there is measured streamflow data at the lake outlet, it could not be used to calibrate and validate the SWAT model as there is water abstraction from Lake Tana for different purposes and there is no information about the amount of water withdrawn for such purposes (Setegn et al. 2008).

ArcSWAT 12.102.19 was used to compile the SWAT input files and SWAT2012 revision 664 was used to run the simulations. Each catchment was divided into sub-basins. Nine LULC units were used as input for the hydrologic models (*Figure 3-2*). Agricultural land is the dominant land use class in the study area (ADSWE 2017). We further split the agricultural land use class into different crop units based on their aggregate areal coverage proportions. Splitting of the agricultural land at this step allows for a detailed consideration of the spatial distribution of the crop units in each HRU (Guse et al. 2015). Cereal crops, vegetables, root crops, and fruit crops are the common agricultural products in Ethiopia. Cereal crops including teff, corn, sorghum, and wheat are the dominant cereal crops both with regard to yields and area coverage. About 24%, 17%, 15%, and 13% of the national agricultural land are covered by teff, corn, sorghum, and wheat, respectively (CSA 2017). To account for the spatial variation of these crops, we calculated their coverage for each catchment based on the respective Administrative Zone of the Amhara Regional State Government (Awi, West Gojam, and South Gondar). The crop

distributions of Awi and West Gojam Zones were used to estimate the percentage distribution of agricultural crops in the Gilgelabay catchment. As the Gumara and the Ribb catchment are entirely located in the South Gondar zone, the percentage distribution of this zone was used to estimate the areal coverage of crop units in these catchments. We applied a random distribution to produce the spatial maps of the catchments based on the percentage distributions of agricultural crop units. Table 1 shows the final land use/land cover percentage distribution in the study catchments.

A static land use map was used in our model setup due to the lack of a time series of land use maps. Wubie et al. (2016), and Central Statistical Agency (CSA 2017) reported that expansion rates of the agricultural land in the study area are 0.45%, and 0.43% per annum, respectively. Thus, a static land use map is a reasonable approximation. For all land use/land cover classes the respective parameter values from the SWAT model database were used, which have similarly been adapted by other studies in the region (e.g. Setegn et al. 2008; Dile and Srinivasan 2014; Woldeesenbet et al. 2017). Planting and harvesting dates as well as potential heat units to reach maturity were adjusted for each land use/land cover class to ensure an appropriate phenological development. Potential heat units to reach maturity were calculated based on average temperature data from the simulation period.

Table 3-1: Areal coverage of LULC types (% of total catchment area)

Crop Type	Percentage of different LULC classes (areal coverage calculated from total catchment area)			SWAT Code
	Gilgelabay	Gumara	Ribb	
Teff	18.50	12.11	16.50	TEFF
Barley	2.74	2.78	3.47	WBAR
Wheat	4.28	0.89	9.10	WWHT
Rice	0.00	18.70	0.00	RICE
Pulses	0.00	8.15	4.26	FPEA
Corn	26.11	4.46	9.40	CORN
Mixed crop land	14.94	14.59	15.37	AGRL
Millet	8.86	0.00	0.00	PMIL
Plantation & natural forest	11.31	6.71	2.10	FRSE
Alfalfa/Grass	2.84	2.84	9.19	ALFA

Crop Type	Percentage of different LULC classes (areal coverage calculated from total catchment area)			SWAT Code
	Gilgelabay	Gumara	Ribb	
Water	0.64	0.06	0.09	WATR
Wetland	0.08	3.46	0.00	WETL
Town	0.02	0.04	0.20	URMD
Range grassland	0.38	12.78	19.50	RNGE
Farm village	9.32	12.43	10.82	URLD

Physical and chemical properties of the soil parameters used for this study were converted into a parameterization for the SWAT model using pedo-transfer functions (PTFs) developed by Saxton and Rawls (2006). Additional information about soil characteristics were collected from different reports (Fisseha and Gebrekidan 2007; Dile and Srinivasan 2014; Ayalew et al. 2015; IUSS Working Group WRB 2015). Each catchment was classified into five slope classes using the digital elevation model. The slope classification was based on the Food and Agricultural Organization (FAO) guideline as follows: 0-2% (foot slope), 2-5% (gentle sloping), 5-8% (sloping), 8-15% (strongly sloping), and > 15% (moderately steep to very steep) (Jahn et al. 2006). To construct a model with high spatial precision, all possible combinations of land use, soil, and slope layers were used to define the HRUs without applying commonly used thresholds (Her et al. 2015) resulting in 1636, 3623, and 795 HRUs for the Gilgelabay, Gumara, and Ribb, respectively.

While daily rainfall and minimum and maximum temperatures data were available for the period from 1980 to 2015, the continuity and consistency of relative humidity, sunshine duration and wind speed data were not reliable. Accordingly, Hargreave's method was chosen for potential ET computation (Hargreaves and Samani 1985). Moreover, the SCS curve number method was used to estimate surface runoff. Further detailed information on the SWAT model including all processes and equations is provided by Neitsch et al. (2011).

2) Model calibration and validation: The most sensitive parameters that have an impact on streamflow were selected using the Sequential Uncertainty Fitting ver. 2 (SUFI-2) in SWAT-



CUP (Abbaspour et al. 2007). The ranges for each parameter were based on the literature (Setegn et al. 2008; Derib 2013; Koch and Cherie 2013; Woldeesenbet et al. 2017). Calibration and validation were carried out using measured streamflow at the catchment outlets (Gilgelabay near Merawi, Gumara near Bahirdar, and Ribb near Addis Zemen). The streamflow data were divided into two periods for each of the streams for calibration and validation. Five years (from 1980 to 1984) were used as a warm-up period to define appropriate initial conditions and to reach equilibrium conditions in the model. Calibration and validation periods in SWAT are selected based on availability of continuous model input data (in our case rainfall) and measured data of the output variables (streamflow in this case) that need to be calibrated/validated. In Gilgelaby catchment, there were considerable missing values in the streamflow and rainfall data between 1985 and 1987. Therefore, we excluded this period (Table 2). A multiple flow segment calibration approach using performance metrics and signature metrics was applied (Pfannerstill et al. 2014a, b; Haas et al. 2016). This calibration procedure was conducted using different packages of R including FME (Soetaert and Petzoldt 2010) to calculate parameter settings based on the Latin Hypercube algorithm and hydroGOF (Bigiarini 2014) to evaluate model performance. Ten sensitive parameters were used in the calibration process, and methods applied to change values for the calibrated parameters are listed in table 3. Six thousand model runs per catchment were conducted with different parameter sets. The best parameter combination was selected based on the Nash-Sutcliffe Efficiency (NSE) of observed and simulated streamflow. Furthermore, the values of Kling-Gupta Efficiency (KGE), Percent Bias (PBIAS), and Standardized Root Mean Square Error (RSR) were considered. The best performing parameter sets found during the calibration period were validated by analysing model output for the validation period. No additional data on the water balance components, e.g. ET, were available for validation.

3) Spatial analysis: The major water balance components such as surface runoff contribution to the stream channel, actual ET, and groundwater recharge from the beginning to the end of the period (calibration and validation periods) were extracted for each HRU on a monthly basis and aggregated on a seasonal basis. These data were mapped to the catchment areas to visualize the spatially distributed model output (Wagner and Waske 2016). The major water balance components were mapped in order to identify potential areas of groundwater recharge. Special attention was given to the impacts of agricultural crop units on groundwater recharge, ET losses as well as surface runoff generation. The groundwater recharge in SWAT can be divided into shallow and deep aquifer recharge (Gemitzi et al. 2017). In this study, groundwater recharge refers to the portion of rainfall that enters the shallow aquifer before it is partitioned into shallow and deep aquifer recharge.

4) Statistical test: the annual hydrologic responses (surface runoff, ET, and groundwater recharge values) of different crop units were tested for significant changes using the Mann-Kendall trend test. The Mann-Kendall (MK) test is a non-parametric test, which has been widely used to test for significant change in time series (e.g. Gautam et al. 2010, Tekleab et al. 2013, Hawtree et al. 2015, Tigabu et al. 2018). Furthermore, the variabilities of water balance components among different crop units and between Gilgelabay, Gumara, and Ribb were tested using a one-way ANOVA test. This test is widely applied in hydrology (e.g. Zegeye et al. 2010, Anibas et al. 2011). A significance level of 5% was applied in this study. Our hypothetical assumptions are that changes in the major water balance components under different crop covers, dry and wet seasons, and between the three catchments were insignificant.

Table 3-2. Warm-up, calibration, and validation periods for the three study catchments.

Catchment	Warm up	Calibration	Validation
Gilgelabay	1980-1984	1988-1996	1997-2011
Gumara	1980-1984	1985-1995	1996-2014
Ribb	1980-1984	1985-1997	1998-2014

Table 3-3: List of sensitive parameters used for calibration of the models

Name of Parameter	Minimum value	Maximum value	Method	Fitted values		
				Gilgelabay	Gumara	Ribb
SCS runoff curve number (CN2)	-15	15	add	-6.13	-7.27	-7.362
Surface runoff lag time (SURLAG)	0.05	24	replace	18.9968	2.8383	11.271
Water capacity of the soil layer (SOL_AWC)	0	1	add	0.1633	0.1547	0.1695
Saturated hydraulic conductivity (SOL_K)	0	1	add	0.6357	0.811	0.8369
Soil evaporation compensation factor (ESCO)	0	1	replace	0.951	0.884	0.7352
Plant uptake compensation factor (EPCO)	0	1	replace	0.044	0.730	0.6285
Groundwater delay (GW_DELAY)	1	100	replace	7.9005	4.0970	4.2153
Deep aquifer percolation fraction (RCHRG_DP)	0	1	replace	0.2806	0.2244	0.2066
Baseflow alpha factor (ALPHA_BF)	0	1	replace	0.2510	0.0902	0.1803
Groundwater revap coefficient (GW_REVAP)	0.02	0.2	replace	0.0252	0.0244	0.0242

### 3.3. Results

#### 3.3.1. Model performance

The model output indicates satisfactory model performance at a daily time step, as the values

of NSE,  $R^2$  and KGE were greater than 0.5 and the PBIAS values were in the range of  $\pm 25\%$  in all three study catchments during both the calibration and validation periods (Moriasi et al. 2007, Table 5). At a monthly time step, the model performance was better in all catchments (Table 5). The good fit of observed and simulated streamflow was also indicated by the flow duration curves (Figure 3-3) and hydrographs (Figure 3-4). The low and middle flows showed a good agreement between the observed and simulated values. On the contrary, the flow duration curve segment from 5% to 20% exceedance probability indicated an underestimation of streamflow by the model, especially in the Gilgelabay and Gumara catchments.

Table 3-4: Daily and monthly model performance measures of different objective functions

Obj. function	Gilgelabay		Gumara		Ribb	
	Calibration (day/month)	Validation (day/month)	Calibration (day/month)	Validation (day/month)	Calibration (day/month)	Validation (day/month)
NSE	0.53/0.71	0.54/0.94	0.65/0.80	0.53/0.79	0.67/0.85	0.67/0.95
KGE	0.59/0.50	0.58/0.62	0.74/0.76	0.62/0.70	0.77/0.77	0.82/0.92
$R^2$	0.75/0.83	0.59/0.83	0.63/0.83	0.63/0.83	0.78/0.86	0.72/0.95
PBIAS	22.4/6.89	23.5/16.95	13.3/16.76	22.1/21.09	3.6/2.80	5/0.04
RSR	0.68/0.54	0.80/0.25	0.65/0.45	0.68/0.46	0.57/0.38	0.58/0.23

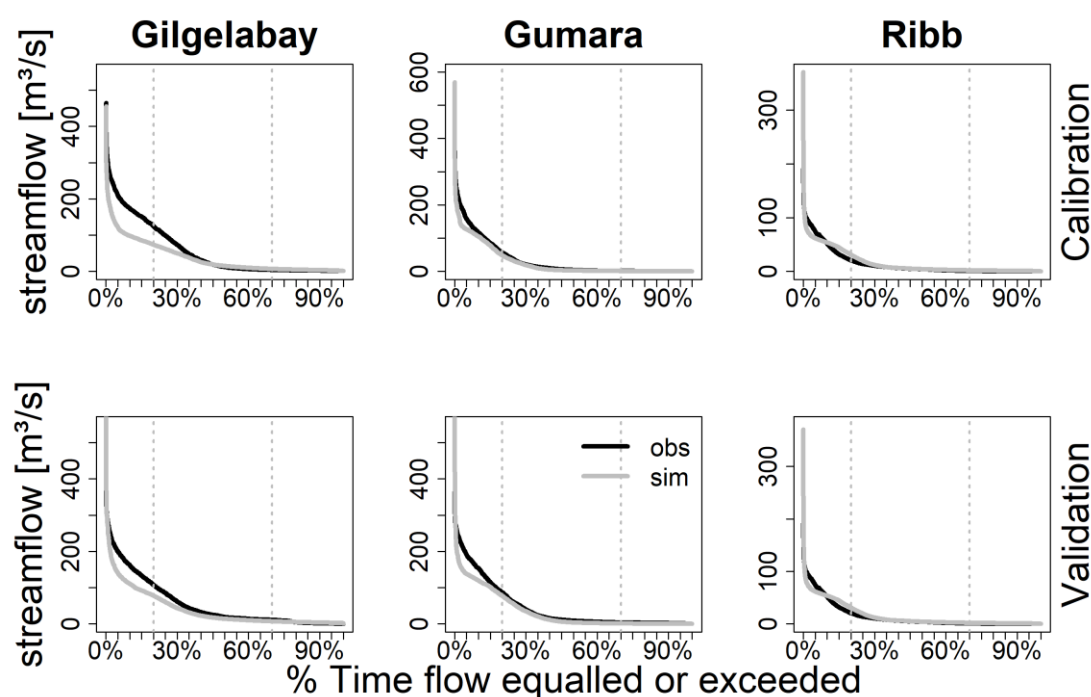


Figure 3-3: Flow duration curves of simulated (sim) and observed (obs) daily streamflow values for calibration and validation periods of the study catchments.

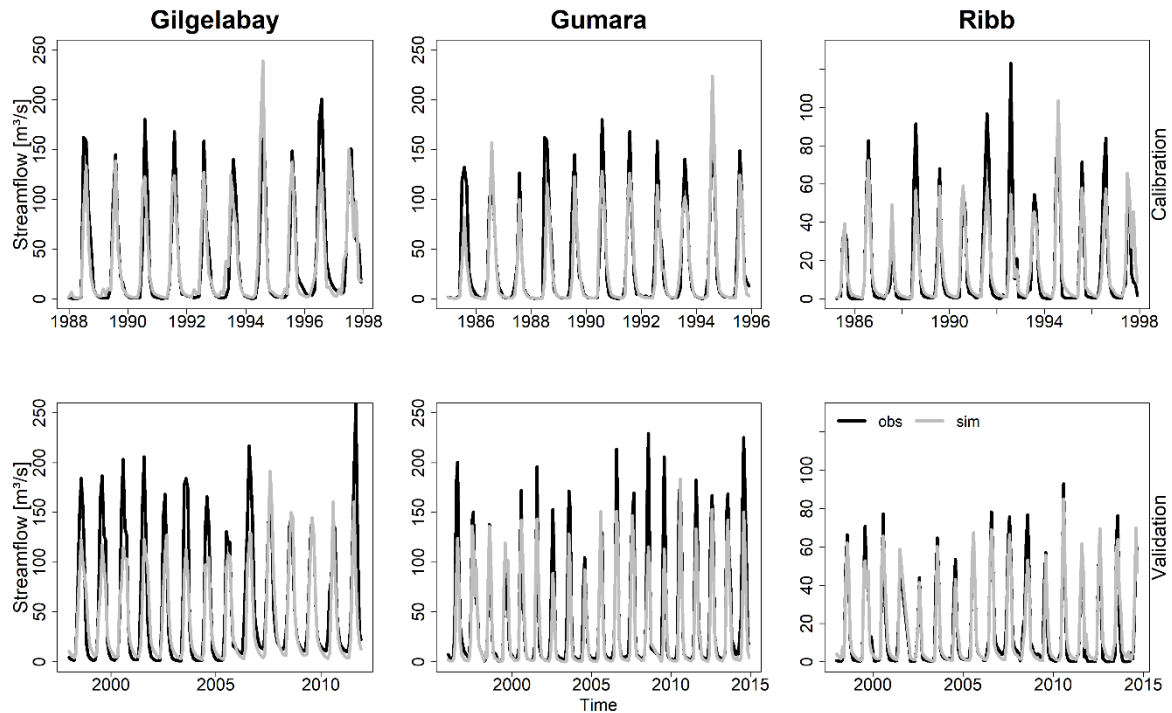


Figure 3-4: Monthly time series plots of observed (obs) and simulated (sim) streamflow of Gilgelabay, Gumara, and Ribb for calibration and validation periods.

### 3.3.2. Impacts of agricultural crops on water balance components

#### 3.3.2.1. General water balance

The water balance can be used to characterize a catchment. Rainfall is the only input variable of the water balance equation in our modeling approach. ET and water yield are the main modelled output components of the water balance. In addition, we analyzed SURQ (surface runoff) and recharge. In all three catchments, more than 75% of the hydrological processes are taking place during the wet (summer) season. The simulated annual values indicated that the mean ET loss of the catchments accounts for 54% (Gilgelabay) and 44% (Gumara and Ribb) of the annual rainfall. Water yield from the HRUs accounted for about 45%, 53%, and 54% of the rainfall in Gilgelabay (759 mm), Gumara (783 mm), and Ribb (832 mm) catchments, respectively. The annual share of water yield from annual rainfall at the HRU level varied within each catchment (*Figure 5*) from 14% to 65% (Gilgelabay), 44% to 65% (Gumara), and 43% to 65% (Ribb). The groundwater return flow contributed more than 50% of the water yield in each catchment. The water yield showed significant spatial variation in Gilgelabay and Ribb

catchments with the south and south-western part of Gilgelabay and eastern and north-eastern part of Ribb catchments experiencing high water yields. In Gilgelabay catchment, rainfall input was taken from four stations and the spatial patterns of ET and water yield followed the rainfall pattern (*Figure 5*). Whereas, in Ribb catchment spatial variations in ET and water yield were caused by the soil and land use variations. Additionally, other catchment properties such as slope affect the spatial variation in water yield. Except for some hot spots with higher water yields, the Gumara catchment had a relatively uniform spatial distribution of water yield when compared to the other two catchments. In general, high water yield corresponds to low ET loss and vice-versa (*Figure 3-5*).

ET loss from different land use and land cover units was generally similar in Gumara and Ribb catchments, although there were a few differences (*Figure 3-6*). Areas covered by natural and plantation forest are areas that have the highest ET and teff has the smallest amounts of average annual water loss by ET in Gumara and Ribb catchments. Gilgelabay catchment differs from the other two with respect to ET loss due to variable rainfall input. In this case, medium density urban settlement areas have the highest and corn has the smallest absolute amount of ET. However, the percentage of ET from rainfall is lower for urban areas (56%) as compared to forests (60%). Other land use/land cover units (forest, urban, wetland, range land, alfalafa, and rural residential) show different ET values also depending on the soil unit as well as slope class (*Figure 3-6*). The majority of the statistical test results showed that the variations in ET values among the crop and other land use classes were statistically significant. The differences in ET values among the different crops and other land use classes could be a result of differences in water uptake, available water capacity, and leaf area indices. However, there were a few exceptional cases that showed insignificant variations, for example, between corn and mixed crop land, barley and pea in Ribb catchment, between pea and mixed crop land in Ribb and Gumara, and between barley and wheat in Gilgelabay catchment. Additionally, ET values vary

based on the spatial distributions of soil units in the Gumara and Ribb catchments. Low ET values are associated with Eutric Liptosol (*Figures 2, 5 and 6*) for both catchments due to the high infiltration capacity of this soil. High ET values cannot be linked to a single soil unit but appear on different HRUs. However, the mean ET values corresponding to Eutric Regosol (in Gilgelabay), Eutric Fluvisol (in Gumara), and Chromic Luvisol (in Ribb) indicated the highest values compared to the ET loss on others soil units in each catchment and Haplic Nitosol was associated with the lowest mean ET in Gilgelabay catchment (*Figure 6*). The inter-catchment comparison indicated that the annual ET losses in Gilgelabay catchment were significantly higher than in Gumara and Ribb catchments with differences varying between 104 mm to 133 mm. These can be explained by the significant variation of rainfall inputs between Gilgelabay and the other two catchments. To the contrary, the differences between Gumara and Ribb ranges from 2 mm to 26 mm and were statistically insignificant.

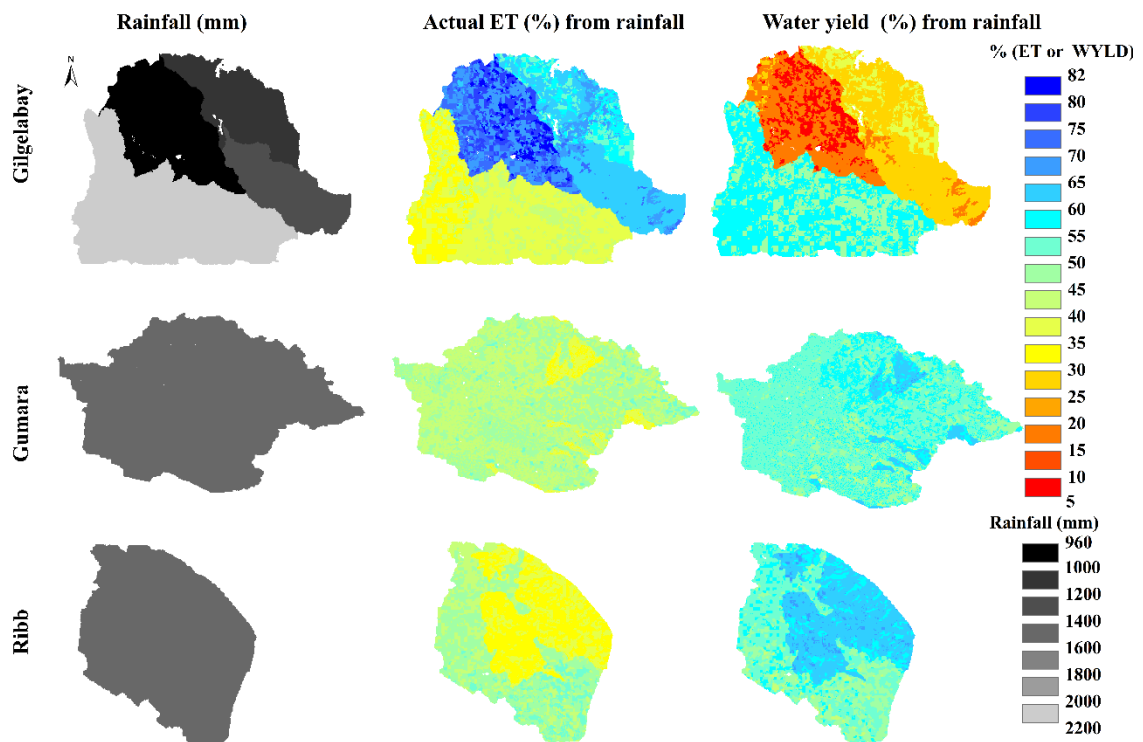


Figure 3-5: Spatial distribution of annual rainfall, ET (%), and WYLD (%) of Gilgelabay, Gumara, and Ribb catchments

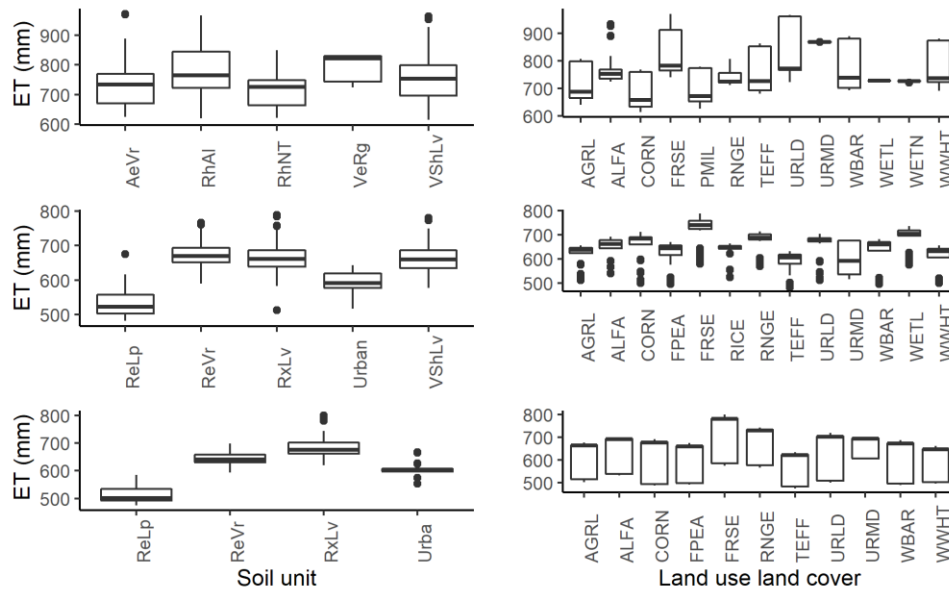


Figure 3-6: Boxplots showing the annual mean actual ET of HRUs for different land use/land cover and soil units of Gilgelabay (first row), Gumara (second row), and Ribb (third row) catchments

### 3.3.2.2. Runoff analyses

Surface runoff varied considerably in time and space in the study catchments (*Figure 7*). In all three catchments about 90% of the total surface runoff was generated during the summer months and the remaining 10% occurred during the other 8 months. The runoff coefficients varied spatially among and within the three catchments due to changes in LULC and rainfall. The annual runoff coefficients (the ratio of total streamflow to rainfall) were 0.32, 0.43, and 0.46 in Gilgelabay, Gumara, and Ribb, respectively. The variability of surface runoff was linked to the LULC, soil type, topography of the area, as well as the associated model parameter values. HRUs covered by medium density urban settlements, farm settlements, and mixed cropland areas had a strong effect on increasing the magnitude of surface runoff. In the Gilgelabay catchment, the mean annual surface runoff of HRUs decreased from farm village, corn, mixed cropland, wheat, millet, barley, teff, permanent wetland, seasonal wetland, alfalfa, and range grassland to evergreen forest. Differences among some agricultural crops and other LULC classes were significant. For example, the changes between corn and other land use and crop classes (forest, wetland, grassland, millet, barley, wheat and teff) vary from 14 mm to 83



mm and all of the changes were significant. Compared to other agricultural crop units, corn and teff had the highest and lowest response in runoff generation. These results can be explained by the lower runoff curve number value in the case of teff and vice-versa in the case of corn. In Gumara and Ribb catchments, surface runoff on urban land cover was the highest. The effects of some of the LULC classes varied between the three catchments. For instance, teff, corn, and generic agriculture HRUs had a slightly different order with regard to the effect on runoff generation between the three catchments. In the Gilegelabay and Gumara catchments, the effect of teff on runoff generation was slightly weaker than corn, while in Ribb catchment teff had a stronger effect than corn (*Figure 3-8*). This implies that besides land use/cover, other HRU properties like soil, slope, and climate cause a combined effect on runoff response. Other LULC classes had similar effects on surface runoff response in all the catchments (e.g. urban, forest, rural settlement, barley, and wheat). In addition to spatial variability, surface runoff varied seasonally (*Figure 3-7 and Table 5*). The annual pattern was mainly defined by the wet season and the surface runoff pattern in the dry season differed considerably from the annual and wet season pattern. Significant differences were observed between the three catchments regarding their runoff responses. Compared to Ribb and Gilgelabay catchments, the vast majority of annual and wet season runoff values of Gumara catchment were higher. The Ribb catchment also showed significantly higher runoff than the Gilgelabay catchment. Therefore, the Gumara catchment is highly susceptible for runoff, whereas Gilgelaby is less susceptible compared to the other two catchments.

Table 3-5: Annual and seasonal water balance components of the three catchments

	Gilgelabay			Gumara			Ribb		
	Annual	Dry season monthly average	Wet season monthly average	Annual	Dry season monthly average	Wet season monthly average	Annual	Dry season monthly average	Wet season monthly average
Rainfall (mm)	1453.0	41.0	281.3	1466.2	22.3	289.0	1475.1	22.3	291.6

	Gilgelabay			Gumara			Ribb		
	Annual	Dry season monthly average	Wet season monthly average	Annual	Dry season monthly average	Wet season monthly average	Annual	Dry season monthly average	Wet season monthly average
SURQ (mm)	108.8	1.1	24.9	190	1.8	44	265.9	1.9	62.7
ET (mm)	785.6	46.8	102.8	650.4	40.6	81.5	644.2	42.3	76.4
WYLD (mm)	648.0	22.5	118.0	728.0	13.0	156.0	752.0	11.0	166.0

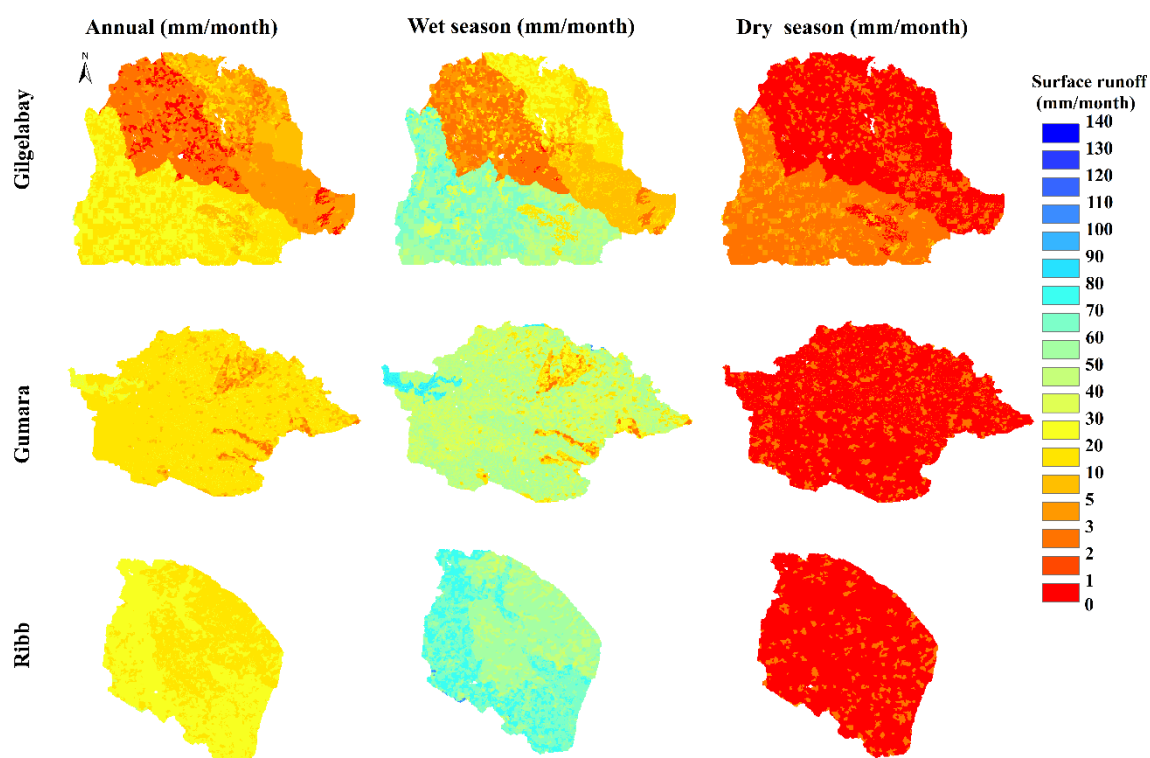


Figure 3-7: Average surface runoff distribution for the year (all months), the wet season (June to September), and the dry season (October to May) for Gilgelabay, Gumara and Ribb catchments

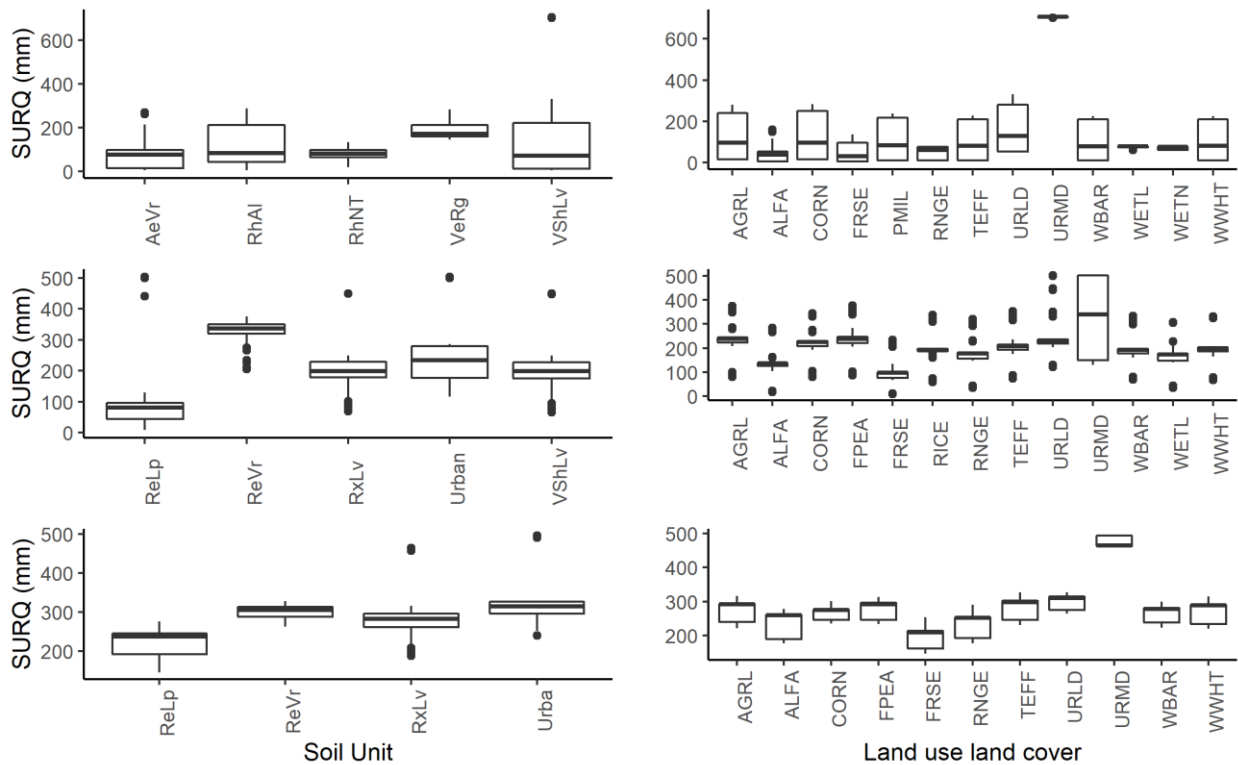


Figure 3-8: Boxplots showing the annual surface runoff (SURQ) of HRUs for different land use land cover and soil units of Gilgelabay (first row), Gumara (second row), and Ribb (third row) catchments

### 3.3.2.3. Recharge Analysis

Quantifying groundwater recharge from agricultural land is important to maintain sustainable water use all over the world. It is highly important in areas like the Lake Tana basin, where most of the streams are perennial and get a substantial amount of their flow from groundwater discharge. There was a high degree of spatial and seasonal variation in groundwater recharge (Figure 3-9). Annual mean recharge (before partitioning into shallow and deep aquifer recharges) values were 561, 560, and 557 mm and the annual mean deep aquifer recharge values were 188, 135, and 115 mm for Gilgelabay, Gumara, and Ribb, respectively. Gumara catchment had the highest mean annual shallow aquifer recharge (457 mm) and Gilgelabay had the lowest (373 mm). However, Gilgelabay had the highest average wet season monthly deep recharge (41 mm). LULC patterns had a strong influence on groundwater recharge rates with a contrasting effect on actual ET (Figures 5 and 9). In combination with soil properties and mean slopes, agricultural crops impacted the groundwater recharge response. The effect of

LULC classes on groundwater recharge varied between the three catchments. In the Gilgelabay catchment, millet and corn had the highest and second highest recharge rates. However, the ranking differed in terms of volumetric contribution. Nearly 50% of the total wet months recharge volume was contributed from corn- and teff-HRUs (corn, 29% and teff, 20%) as they covered a larger portion of the catchment (Table 1). These are mostly found in the southwestern and western parts of the catchment that receive high amounts of rainfall (*Figure 3-5 and 9*). To the contrary, corn was among the LULC classes that had a low recharge rate in the case of Gumara (*Figure 3-10*). This indicated that other catchment properties also played a role in influencing recharge rates. In the Ribb catchment, agricultural areas covered by teff had the highest average annual (614 mm) recharge to the shallow aquifer. Urban areas had the lowest groundwater recharge in both Gumara and Ribb catchments (*Figure 3-10*). For the Gilgelabay catchment, the mean annual groundwater recharge in medium density urban areas was higher compared to other land uses due to the highest rainfall input, but its percent share of rainfall was the lowest of all LULC classes (26%). For other LULC, 28% to 44% of the rainfall recharged the shallow aquifer. As a whole, our statistical test results indicated that there were significant variations in the rates of recharge among the different agricultural crops and other LULC classes between and within the three catchments. Therefore, our initial hypothetical assumption (no significance changes on the recharge rates among different land cover units) was rejected. For example, the recharge rates of forest areas were significantly lower than the recharge rates of agricultural areas (teff, barley, wheat, etc.) for all the three catchments. Comparing recharge rates among the agricultural crop units showed that cereal crops (barley, corn, rice, teff, and wheat) had significantly higher recharge rates than leguminous (pea) and mixed cereal crop units. In addition to the LULC, the impact of soil units on recharge rate was obvious in all catchments. Areas covered by Eutric Regosols and Eutric Leptosols were identified as high groundwater recharge areas. In Gilgelabay catchment, areas covered by

Eutric Regosols had the highest groundwater recharge rate whereas Haplic Nitosols had the lowest. In both Gumara and Ribb catchments, Eutric Liptosols had the highest average groundwater recharge, while Eutric Fluvisols and Chromic Luvisols had the lowest recharge (Figure 3-10).

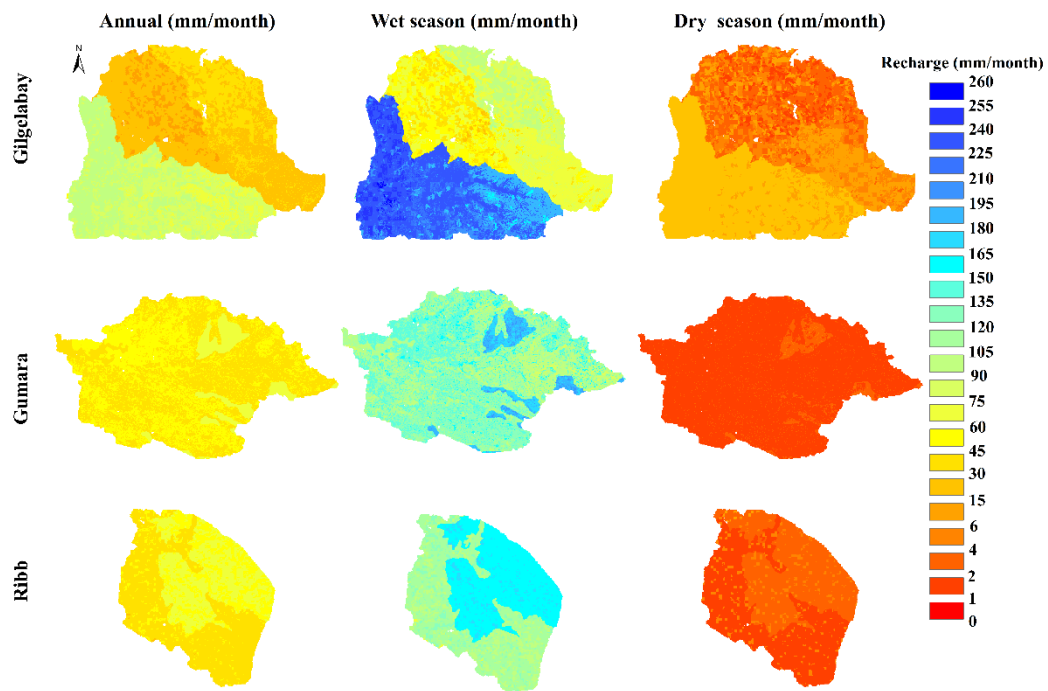


Figure 3-9: Average groundwater recharge distribution of annual, wet season (June to September), and dry seasons (October to May) values (in mm) per month for Gilgelabay, Gumara, and Ribb catchments

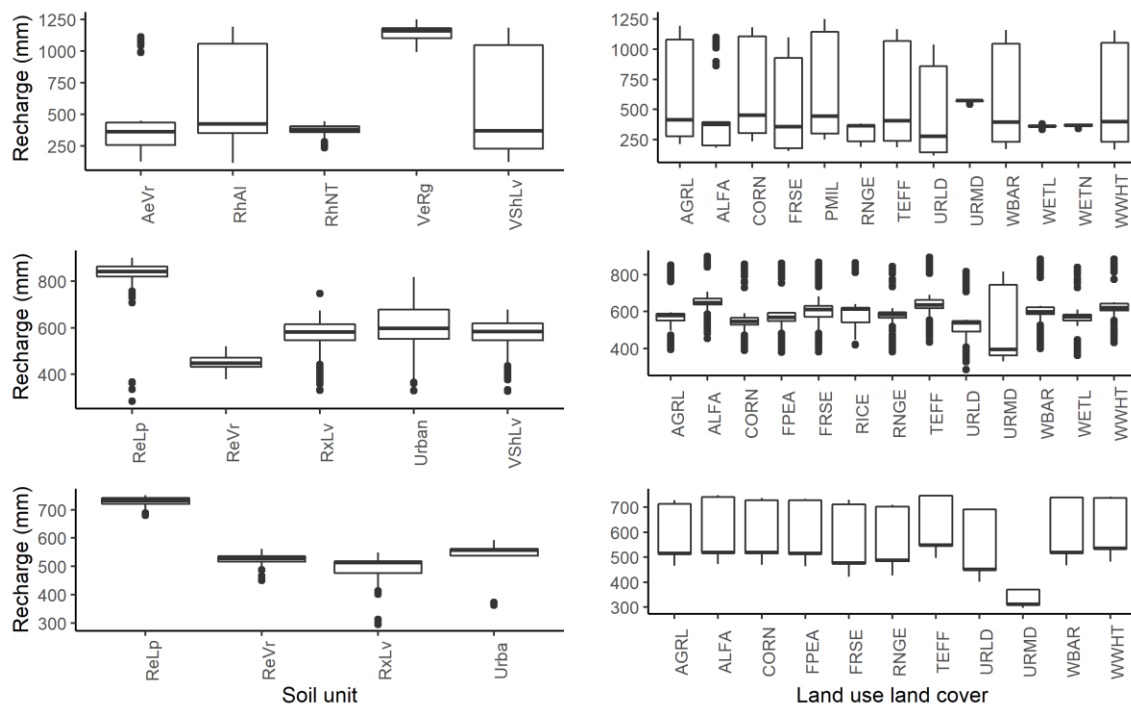


Figure 3-10: Boxplots showing the annual groundwater recharge to the shallow aquifer for different LULC and soil units of Gilgelabay (first row), Gumara (second row), and Ribb (third row) catchments

#### 3.3.2.4. Temporal analysis

Annual values of the hydrologic responses for dominant crop classes were analyzed. The inter-annual variabilities of these hydrologic responses are mostly driven by changes in the weather input (*Figure 11*). The annual values of water yield, ET, surface runoff, and groundwater recharge are a function of the temporal pattern of the rainfall inputs. As we used a static land use map for the modeling, most of the changes induced by agricultural crops are seasonal (*Figures 7 and 9*). The Mann-Kendall (MK) trend test was applied to test for significant changes on inter-annual variabilities of the hydrologic fluxes. The MK test results showed that there were no significant changes on the inter-annual variabilities of water balance components ( $p\text{-value} > 0.05$ ). In general, ET is less affected by the inter-annual rainfall variability as compared to the other variables. However, a rainfall deficit (e.g. in 1991) has a stronger effect

on ET than a rainfall surplus (e.g. 2006).

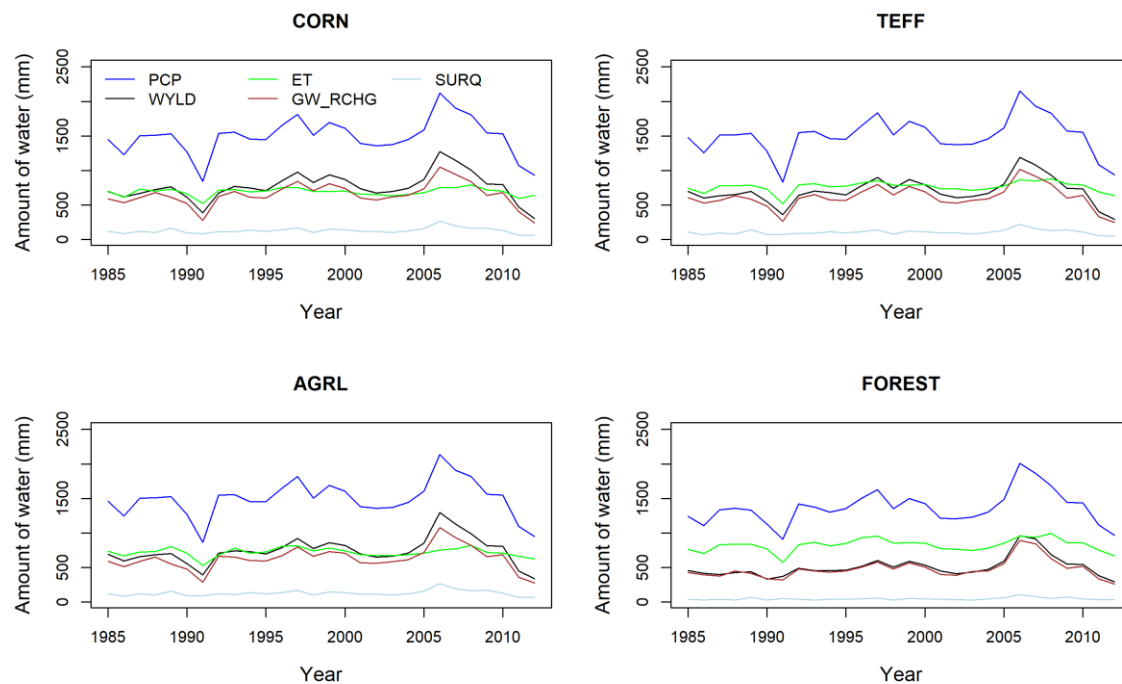


Figure 3-11: Annual temporal distribution of rainfall (PCP), water yield (WYLD), actual evapotranspiration (ET), groundwater recharge (GW-RCHG), and surface runoff (SURQ) values under different LULC conditions in Gilgelabay catchment

### 3.4. Discussion

In this study, the impacts of agricultural crop units on the spatial and seasonal variation of the major water balance components were analyzed for the first time in the Gilgelabay, Gumara, and Ribb catchments of the Lake Tana Basin, Ethiopia. The effects of HRU components (LULC, soil, and slope) on catchment water yield, ET, surface runoff, and groundwater recharge were assessed. A calibrated SWAT model was used to simulate the aforementioned water balance components from 1985 to 2014 assuming the recent temporal change on agricultural crop cover is minimal (CSA 2017). The dominant agricultural classes such as cereals, leguminous, and mixed cereals together with other land use classes were considered in the model. Our model performances were evaluated based on flow duration curves and hydrographs of simulated and observed streamflow values (*Figure 3-3 and Figure 3-4*). The patterns of simulated and observed streamflows indicated consistency between each other for

both calibration and validation periods. However, there are slight differences on the statistics of the model efficiencies reflecting the temporal dynamics of streamflow data (Fohrer et al., 2002). The model efficiencies were comparable with results of Setegn et al. (2008) and Woldeesenbet et al. (2017). However, our analysis of the flow duration curves indicates that there is a disparity between the measured and modelled high flows (between 5% to 20% exceedance probabilities with an RSR value 1.41) in the Gilgelabay catchment. This disparity on the high flow segment might be linked to the limitation of the curve number method, as the SCS-curve number method used in the SWAT model does not consider the duration and intensity of rainfall (Nie et al. 2011, Woldeesenbet et al. 2017). The Nash-Sutcliffe Efficiency (NSE) for Gilgelabay catchment showed the lowest performance (0.53) compared to the other two catchments (Table 4), which also pointed to the disparity on the high flow segment of the FDC as NSE is known to give higher weights to high flows than to low flows (Guse et al. 2017). The underestimation of high flows can, to a lesser extent, be seen in the FDC for Gumara, whereas the FDC for the Ribb catchment indicates a much closer match.

The spatial and seasonal distribution of the modelled hydrological components groundwater recharge, surface runoff, water yield, and ET was analyzed. However, an independent validation of the spatial distribution of ET and water yield was not possible due to a lack of measured data. The accuracy of the derived patterns of ET and water yield relies on the model validity, which was tested with measured streamflow data at the catchment outlet using a multi-metric approach and flow duration curves. In addition, the seasonal development of the leaf area index was checked for all land use classes to provide further confidence in the model calculation. In our study, the Hargreaves method (Hargreaves and Samani 1985) was used to compute potential evapotranspiration, which has been applied in several SWAT model studies in Africa (e.g, Setegn et al. 2008; Notter et al. 2012; Woldeesenbet et al. 2017). In addition, Odusanya et al. (2019) compared the Hargreaves, the Penman–Monteith, and the Priestley–



Taylor method in SWAT for a catchment in Nigeria, and found that the ET values computed using the Hargreaves method showed good agreement with satellite based ET patterns. These studies provide further confidence in the accuracy of the derived ET patterns.

Likewise, the validity of the simulated surface runoff and groundwater recharge were not verified independently. However, model outputs of the current study were compared to similar studies in the region. In this study, the runoff coefficients calculated from the simulated discharge were 0.32, 0.43, and 0.46 for Gilgelabay, Gumara, and Ribb, respectively. A study conducted on the effects of the floodplain on river discharges into Lake Tana by Dissie et al. (2014) reported that the runoff coefficient in the upper catchments of the Lake Tana basin vary between 0.23 and 0.81 with an average value of 0.5. The simulated runoff coefficients from our study are within this range. Furthermore, the ratios of average surface runoff to total streamflow found in our study were 0.23, 0.28, and 0.35 for Gilgelabay, Gumara, and Ribb, respectively. In support of these values are the findings by Jemberie et al. (2016), who reported that the average surface runoff to total streamflow ratio of the Lake Tana basin is 0.28.

In this study, the modelled water balance components showed a high degree of variation in their spatial and seasonal distribution. These spatial variations are due to variations in land use and land cover types, soil permeability and porosity, and slope class of the area, as well as varying climatic input data. The seasonal variations are induced due to the temporal variation of rainfall and variation in the canopy coverage of the different crops during the wet and dry seasons. The water balance analysis indicates that different HRU components (LULC/crop, soil, and slope classes) do not equally affect the catchment's hydrology. The influence of slope is smaller when compared to soil and crop types. When the groundwater recharge and surface runoff generation were analyzed for different slope classes under the same land use (teff) and soil (Eutric Liptosol), the observed variation was about 1%. To the contrary, the groundwater recharge and surface runoff showed significant variations (from 47% to 50%) when Eutric

Liptosols is changed to Haplic Luvisols for an HRU with teff and foot slope. Thus, variations in vegetation and soil types have a higher influence than slope in our simulation results. The changes in the water balance components were also significant between different agricultural crop units. Similarly, Li et al. (2019) reported a substantial impact on the hydrology of Wei River basin due to expansion of cropland. As an example, in the Gumara and Ribb catchments, the groundwater recharge over time in areas covered by teff was significantly higher than the groundwater recharge in areas covered by other agricultural crops. In the Gilgelabay catchment, HRUs with agricultural area covered by millet have the highest average groundwater recharge followed by agricultural land covered by corn. These higher recharge rates on teff and millet crop cover areas might be linked to the lower water demand for evaporation as the water interception capacity and leaf area index values are lower than in other LULC units like forest and shrub lands. Moreover, forest cover and shrub land areas had less recharge compared to cropland because a larger amount of water was evapotranspired. The results are in agreement with the findings of Nie et al. (2011) who studied the impact of land use and land cover change on the hydrology of the upper San Pedro watershed. Their scenario-based simulation indicated that the baseflow/percolation decreased when grassland was replaced by shrub land. A study by Gumindoga et al. (2014) on predicting streamflow for land cover changes in the Gilgelabay catchment also reported a higher groundwater recharge on agricultural areas than forest areas. Their findings are in agreement with the current study. The other crop types also exhibit different recharge rates based on the daily water needs and the phenological stage. Cereal crops like millet, teff, wheat, and barley show relatively good recharge due to less water interception and transpiration demand even in a full development stage when compared to mixed crops, pulses, and rice. Our results are in agreement with research findings of Fohrer et al. (2001) who reported that the baseflow was increased for an area covered with barley compared to forest cover due to the lower water interception capacity

of barley in Germany. Therefore, it can be concluded that cereal crops such as teff, barley, wheat, and millet enhanced the groundwater recharge by reducing ET and surface runoff in the three catchments. Additionally, our runoff analysis results indicated that agricultural crops such as pea increased runoff when compared to other agricultural crop classes. Hence, an expansion of agricultural crops like pea affects the water availability in the region, which should be considered during decision making processes.

The spatial dynamics of the hydrologic components for Gilgelabay catchment showed similar patterns to the differing rainfall input. The sub-basins located on the southern and southwestern part of the catchment have the highest amount of rainfall and are characterized as a high groundwater recharge and surface runoff zone (*Figure 3-5, 7, and Figure 3-9*). This part of the catchment which accounts for about 15% of the total area has the highest runoff response due to high rainfall intensity, steep slope classes, and Haplic Alisols. A secondary clay minerals assemblage domination is a typical feature of Haplic Alisols, which could cause high runoff response (IUSS Working Group WRB 2015). In the Gumara and Ribb catchments only one rainfall station was used, so that LULC and soil units have more influence on the spatial patterns of hydrologic components than rainfall. There is a high degree of spatial variability of the hydrological processes as the soil units change from Eutric Leptosols (mainly dominated by gravel and sand, and belongs to hydrologic soil group B) to texturally clay dominated Eutric Vertisols and Chromic Fluvisols, which belong to hydrologic soil group C and D, respectively. The northern and southeastern parts of Gumara and Ribb catchments, which are covered by Eutric Leptosols (hydrologic soil group B), are relatively good groundwater recharge zones. The reason for this is that Eutric Leptosols are sand dominated and characterized by many coarse fragment soil particles (IUSS Working Group WRB 2015). The highest amount of surface runoff occurred on areas covered by Eutric Fluvisols (hydrologic soil group D). Thus, soil class boundaries are good benchmarks to map groundwater recharge zones in the

catchments (*Figure 9*). With respect to LULC, agricultural areas covered by teff and wheat have the highest groundwater recharge potential due to their low leaf area index, which allows for more infiltration. Low density rural settlement areas are characterized by the lowest groundwater recharge and highest surface runoff. The higher surface runoff which is seen in settlement areas due to impervious surfaces is well supported by the literature: Zhang et al. (2016), who studied hydrological responses to land use change scenarios under constant and changed climatic conditions of the Heihe River basin, China, reported that developed lands produced higher runoff than cultivated and grassland and Wagner et al. (2016) linked an increase in urban area to an increase in water yield on the sub-basin level in a meso-scale catchment in India and, the increase in runoff to the onset of monsoon (Wagner et al. 2016). The absolute values of ET decreased from forest cover to cultivated land for all three catchments due to the high canopy storage, leaf area index, and transpiration demand for forest cover compared to cropland (Nie et al., 2011). In the case of the Gilgelabay catchment, urban and rural settlements have the highest average annual actual evapotranspiration due to high rainfall input. However, their percentage shares from the total rainfall (urban, 40% and rural settlements, 56%) are still less than forest (60%) (*Figure 6*).

The overall mean annual ET loss from annual rainfall accounts for 54% in Gilgelabay and for 44% in Gumara and Ribb. Setegn et al. (2008) reported that more than 60% water is lost as ET. This variation could be due to the differences in the model setups and periods of simulation, as well as variation of the LULC data that were used. Setegn et al. (2008) used a single SWAT model for the whole Lake Tana Basin with 10%, 20%, and 10% threshold values of LULC, soil, and slope, respectively, whereas the current study was carried out by setting up three independent models for Gilgelabay, Gumara, and Ribb catchments using highly refined LULC data (with no threshold limit for LULC, soil, and slope). Our findings showed significant dynamics of the hydrologic components between the wet and dry seasons. More than 90% of

the groundwater recharge and surface runoff and about 49% of the ET took place during the wet season. This implies that the influence of rainfall for the hydrologic processes in the region is significant. The total streamflow values are dominated by the baseflow in all the three catchments (73%, 62%, and 60% of the total streamflow in Gilgelabay, Gumara, and Ribb, respectively). Setegn et al. (2008) reported a value of 59% for the Gilgelabay catchment. The higher baseflow contribution for the Gilgelabay catchment in this study may be due to the higher fitted values of SURLAG and ALPHA\_BF, which affect the runoff and baseflow response. Moreover, baseflow is a function of catchment area, and geomorphological, geological, and hydrogeological parameters of the catchment (Wosenie et al. 2014). In this study, the effect of catchment area on baseflow contribution was reflected. The Gilgelabay catchment, which is the largest of the three, had the highest baseflow contribution, whereas the Ribb catchment, which is the smallest catchment, had the lowest baseflow contribution to streamflow. The annual deep groundwater recharge accounts for 13%, 9%, and 7% of annual rainfall for Gilgelabay, Gumara, and Ribb, respectively. The order of the amount of deep groundwater recharge is in agreement with the order of the fitted values for RCHRG\_DP in our model (Table 3). These results are in line with Wosenie et al. (2014) who reported that the Gilgelabay catchment had higher groundwater recharge rates than the Gumara catchment.

### **3.5. Summary and conclusion**

In this study, the impacts of agricultural crops and other LULC classes on the major water balance components were investigated in the Gilgelabay, Gumara, and Ribb catchment, Lake Tana basin, Ethiopia.

Our findings show that the spatial and seasonal values of ET in the Gilgelabay catchment were significantly different from the values in Gumara and Ribb. Likewise, the groundwater recharge and surface runoff values revealed significant spatial and seasonal variations between the three catchments. To the contrary, the ET values between Gumara and Ribb catchments

showed insignificant variations. Compared to Gilgelabay and Ribb, the Gumara catchment showed high susceptibility for runoff, whereas Gilgelaby is less susceptible compared to the other two catchments. Besides, the results showed that there were no significant differences in the inter-annual variabilities of ET, surface runoff, water yield, and groundwater recharge.

In summary, our findings highlight the significance of considering agricultural crop classes in the application of hydrologic models, which often rely on only one generic agricultural class. The vast majority of the agricultural crop classes had a significant effect on the water balance components. On the one hand, cereal crops had higher rates of groundwater recharge compared to others like leguminous and mixed crops. On the other hand, leguminous crops like peas had significant impact on increasing runoff generation. Therefore, expansion of agricultural crops like pea may be discouraged as they favoured surface runoff generation, which in turn may lead to a higher erosion risk. In this regard, the present research approach could be extrapolated to similar catchments in Ethiopia and other African countries where agricultural land use dominates.

Moreover, for future impact assessment of agricultural crops on water balance components, a time series LULC could provide further insights into inter-annual impacts on the water resources. In addition, it is recommended to incorporate climate change in future assessments of groundwater and surface water dynamics to derive sustainable solutions for the future.

#### **4. Modeling spatio-temporal flow dynamics of groundwater-surface water interactions of the Lake Tana Basin, Upper Blue Nile, Ethiopia**

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## **Abstract**

The Ethiopian government has selected Lake Tana basin as a development corridor due to its groundwater (GW) and surface water (SW) potential. However, there is little knowledge about the flow dynamics of GW and SW in the Lake Tana basin, Ethiopia. Mostly, water from the aquifer system is extracted in an unplanned and unregulated manner that could result in over-pumping of the aquifer system. Therefore, this study aims to investigate the flow dynamics of GW-SW systems on a spatio-temporal basis and to assess if there is a hydraulic connection between GW and SW systems in three of the main catchments (Gilgelabay, Gumara and Ribb) that drain into Lake Tana. The SWAT-MODFLOW model, which is an integration of SWAT (Soil and Water assessment Tool) and MODFLOW, is used as a hydrologic model with coupled surface and sub-surface flow is necessary to investigate GW-SW interactions. The results reveal that aquifer and the stream network systems are hydraulically connected to each other in all three catchments. In the Gilgelabay catchment the flow from the aquifer to the river cells dominates, whereas in Gumara and Ribb, the main flow is from the river cells to the aquifer system. The daily GW-SW interaction rate is more dynamic than the annual one. Moreover, the flow pattern differs in the three catchments due to spatial variations of the aquifer parameters and morphological heterogeneity among the catchments. The average groundwater recharge to the MODFLOW grid cell shows high seasonal variation in all three catchments. For instance, in the Gumara catchment, the mean annual groundwater recharge to the MODFLOW grid cell is about 80 m<sup>3</sup>/day, whereas the wet season mean is about 220 m<sup>3</sup>/day, and the dry season mean is only 20 m<sup>3</sup>/day.

**Keywords:** Coupling, flow dynamics, groundwater-surface water interaction, SWAT-MODFLOW, hydraulic head, spatio-temporal, seasonal variation, and recharge



#### **4.1. Introduction**

Water availability and water quality are main challenges of the 21st century due to a growing water demand. The challenge is twofold for developing countries like Ethiopia because of a limitation in technology and financial resources to invest in water resources development. Thus, groundwater (GW) is the only reliable water supply option for most rural areas in Africa to meet the dispersed demand (Hiscock 2011). However, mostly extraction of water from the aquifer system is not planned and or regulated, so that it could result in over-pumping of the aquifer system. Therefore, a comprehensive understanding of watershed hydrology with particular emphasis on the interaction of GW and surface water (SW) is essential for sustainable water management in a watershed (Bailey et al. 2016).

So far, several studies have focused on modelling GW and SW interactions; Jayasekera et al. (2011) studied GW stress and vulnerability in rural coastal aquifers using an empirical model known as modified DRASTIC (Depth to the GW table, net GW Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone media, and hydraulic Conductivity of the aquifer). Sutanudjaja et al. (2011) had constructed a large scale MODFLOW transient GW model coupled with a distributed land surface model for the Rhine-Meuse basin based on readily available global datasets. Ahring and Steward (2012) studied the GW-SW interaction using the spatial distribution of phreatophytes. Pfannerstill et al. (2014) investigated GW processes in a German lowland catchment and improved their representation in the SWAT model. Duvert et al. (2015) analyzed the variability of GW within the aquifer system and assessed the response of the aquifer system to high and low frequency rainfall variations. Goderniaux et al. (2015) studied the uncertainty of climate change impact on GW reserves, and Gemitzi et al. (2017) developed an empirical monthly GW recharge equation based on modelling and remote sensing data to predict potential climate change impacts.

Moreover, strong efforts have been conducted to integrate SWAT (Soil and Water Assessment Tool) (Arnold et al. 1998) and MODFLOW (Harbaugh et al. 2000) to analyse GW and SW interactions. For example, Guzman et al. (2015) developed an integrated SWAT and MODFLOW model (“SWATmf”) to improve the assessment of impacts of natural and anthropogenic stressors on both SW and GW resources at the watershed scale, and Izady et al. (2015) applied the combined SWAT-MODFLOW model to estimate GW recharge for a catchment located in northeast of Iran. Bailey et al. (2016) developed the coupled SWAT-MODFLOW model, that was upgraded later into the graphical user interface model SWATMOD-Prep (Bailey et al. 2017). Ehtiat et al. (2018) integrated SWAT, MODFLOW, and MT3DMS to investigate how SW conditions affect the quality of the GW system in a non-coastal aquifer. Chunn et al. (2019) studied the impacts of climate change and water withdrawal on the GW-SW interactions in West-Central Alberta using the integrated SWAT-MODFLOW model. Similarly, Park et al. (2019) developed a QGIS-based graphical user interface SWAT-MODFLOW model for Middle Bosque River Watershed in central Texas. However, as compared to the number of catchment modelling studies and their regional coverage, more efforts are needed to assess GW-SW interaction in different parts of the world.

Ethiopia is one of those regions where GW resources are under severe pressure and widely used even though the system is not yet well understood. In the Lake Tana basin, low flows are expected to decline by up to -61% under the A1B and B1 emission scenarios for 2050s (Taye et al. 2015). Consequently, it is assumed that more GW will be used to overcome the freshwater constraint in Ethiopia in general and in the Lake Tana Basin in particular. According to the Ethiopian government growth and transformation plan, agriculture irrigated from GW sources is expected to cover 2 million hectare by 2020 (Kebede 2012). Due to its proximity to the point of demand, GW provides 90% of the domestic water supply, 95% of the industrial use, and a small proportion of irrigation water demand. In general, 80% of the total national water supply

comes from GW (Kebede 2018). Previous hydrological studies focused on the surface water use and hydrologic balance and do not adequately address issues of GW, particularly in the context of combining SW–GW models in the Lake Tana Basin. For example, Setegn et al. (2008) applied SWAT2005 to model the hydrologic balance of the Lake Tana Basin with the main objective to test the performance and feasibility of SWAT model in predicting streamflow in the basin; Seyoum et al. (2013) used a flow forecasting model (HEC–HMS) for their rainfall-runoff prediction in Gumara and Ribb catchments; Gebremicael et al. (2013) investigated the long-term variability of rainfall, runoff and sediment fluxes, and causes of changes in runoff and sediment load of the Upper Blue Nile; Dessie et al. (2015) analyzed the daily water balance of the Lake Tana using a simple rainfall-runoff model; Worqlul et al. (2015) studied the availability of surface water for irrigation use; Dile et al. (2016) focused on the implications of water harvesting intensification on upstream–downstream ecosystem services of the Lake Tana Basin, and Woldesenbet et al. (2017) focused on land use/cover change impact on hydrologic responses of the Lake Tana and Beles sub-basins. Conway & Hulme (1996) reported that there is high SW stress in the Upper Blue Nile region over time due to global warming. Because of the SW stress, nowadays the Ethiopian government focuses on using more GW for different purposes than before (MoW 2011). A recent study conducted by Woldesenbet et al. (2017) revealed that the average annual baseflow and percolation decreased gradually, to the contrary the average annual surface runoff increased due to land use and land cover changes of Tana and Beles sub-basins in Ethiopia between 1986 and 2010. Dile et al. (2018) reviewed hydrological research papers that have been focusing on the Upper Blue Nile basin and they recommended that future research shall focus on the application of coupled models to predict multiple outcomes across multiple spatial and temporal scales in the basin as most of the previous studies have been focused on single model applications to estimate a single output such as streamflow or sediment loss at the outlet of a catchment. Chebud and Melesse

(2009) applied a numerical model to investigate the groundwater flow system in the Gumara catchment and they identified that there is a research gap on the spatial and temporal distribution of percolation in the Gumara catchment in particular, and in Lake Tana Basin in general. A hydrologic modelling study that applied the SWAT model in the catchments of Gilgelabay, Gumara, and Ribb showed that the flow systems are strongly influenced by GW (Tigabu et al. 2019). Therefore, the application of a coupled hydrologic model that is capable of simulating SW and GW and their interaction is required in areas like the Lake Tana Basin, which often lack piezometric information to characterize local GW and SW interactions.

Thus, we apply a coupled SWAT-MODFLOW model (SWAT: Arnold et al., 1998; Arnold & Fohrer 2005; MODFLOW: Harbaugh 2005; coupling interface SWATMOD-Prep: Bailey et al. 2017) to enhance our understanding of the spatio-temporal interactions of GW and SW in the Lake Tana basin, Upper Blue Nile, Ethiopia. The specific objectives of this study are:

- to investigate if the aquifer and stream network systems are hydraulically connected,
- to assess GW-SW exchange rates at river cell and sub-basin levels, and to identify the spatial extent of GW discharge and recharge areas,
- to determine if there are differences in GW-SW interactions between the three catchments,
- and to understand the spatial variability of the GW hydraulic head.

## **4.2. Materials and Methods**

### **4.2.1. Study area**

The Lake Tana basin, which is the second largest sub-basin of the Blue Nile, is situated in the north-western part of Ethiopia (*Figure 3-1*). The catchment area of the basin at the outlet of Lake Tana is 15,321 km<sup>2</sup>. The lake has a surface area of 3,156 km<sup>2</sup> that covers about 20% of the total catchment area (Alemayehu et al. 2010, Tigabu et al. 2018). The catchment has a very

diverse topography with an altitude ranging from 1322 m to 4111 m above sea level (Tigabu et al. 2018). Moreover, the lake is shallow with a maximum depth of 15 m and characterized by a steep slope at the borders and by a flat bottom (Kebede et al. 2006). It comprises about 50% of the country's fresh water (Costa et al. 2014). The Blue Nile River originates from Lake Tana. More than 40 rivers and streams flow into Lake Tana with a mean annual inflow of 158 m<sup>3</sup>/s (Alemayehu et al. 2010), but 86% of the water originates from three major rivers: Gilgelabay, Gumara, and Ribb (Alemayehu et al. 2010). The annual volume of surface outflow measured at the lake outlet is 4 billion m<sup>3</sup> (*Figure 3-1*).

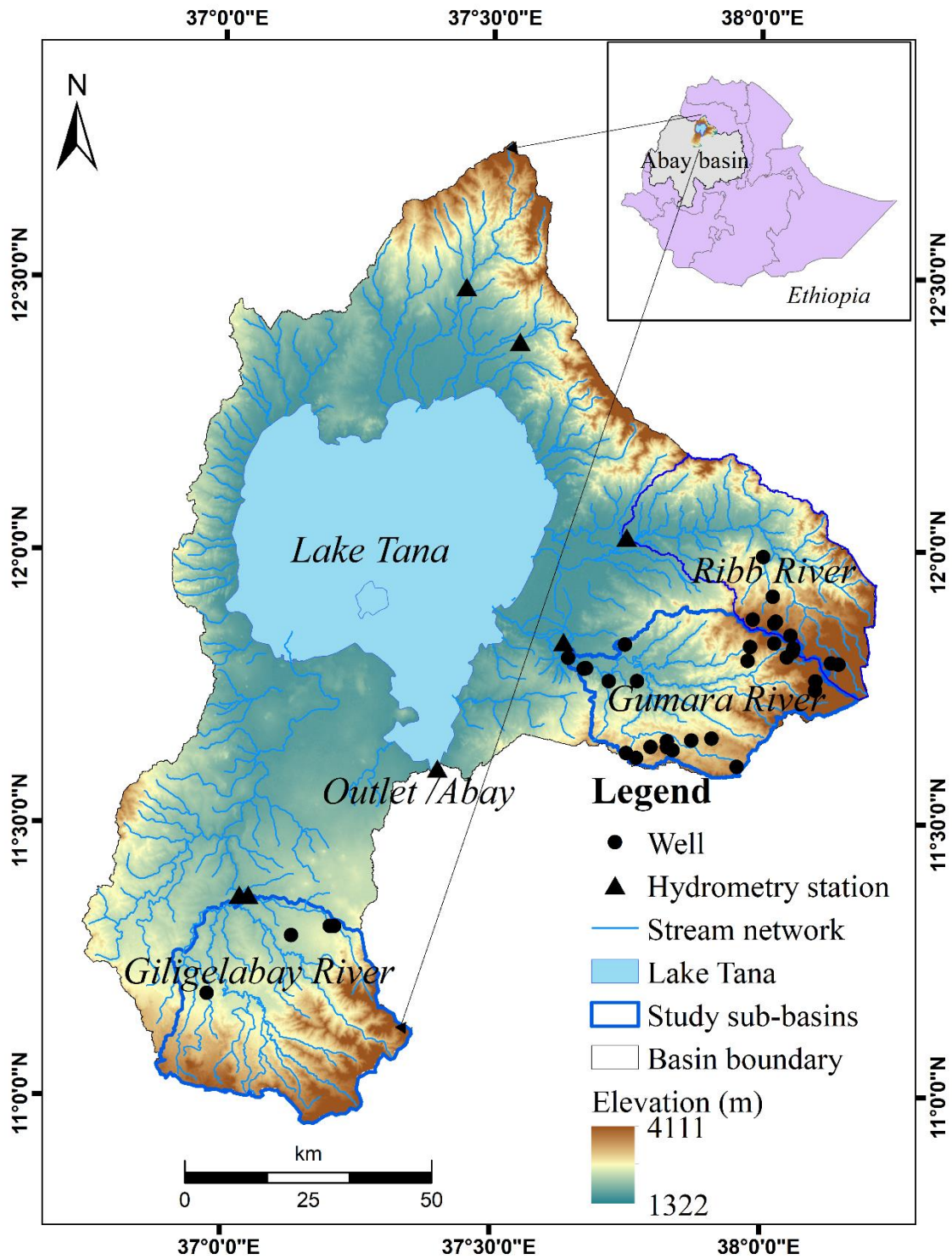


Figure 4-1: Location map and major tributaries of Lake Tana including the three study areas and river gauging stations

#### 4.2.2. Model input data

We used a calibrated and validated SWAT model (Tigabu et al. 2019) that is based on a 30 m by 30 m resolution DEM (SRTM 1 arc-second global digital elevation model; USGS 2016), a

soil map and a land use map from the Amhara Design & Supervision Works Enterprise (ADSWE 2017). Daily weather data including rainfall and maximum and minimum temperature were available from the National Meteorological Service Agency (NMA 2016). The SWAT model with its sub-basins, hydrologic response units (HRUs), and river network shapefiles were inputs to the coupled SWATMOD-Prep model (Table 1). Moreover for the parameterization of MODFLOW, maps of initial GW head were prepared by inverse distance weighted (IDW) interpolation of water level data from hand-dug wells and boreholes that were collected from Amhara Water Works Construction (AWWCE 2016) and Tana Basin Development Authority (TBDA 2016). Saha et al. (2017) have applied the same approach in their modelling study of temporal dynamics of groundwater-surface water interactions for a watershed in Canada. Hydraulic conductivities, specific storage, and specific yield values were assigned to each soil unit based on previously published values (Morris and Jonson 1967), and river bed material K (default value of MODFLOW) were used as input data for the MODFLOW model. The horizontal and vertical anisotropy factors for all materials were set to 1, assuming that these anisotropies were not changing both horizontally and vertically. The streamflow data from gauging stations Gilgelabay near Merawi, Gumara near Bahirdar, and Ribb near Addis Zemen for the years 1980 to 2014 were provided by the Ministry of Water, Irrigation and Electricity of the Ethiopian Government (MoWIE 2016) to validate the coupled model.

#### 4.2.3. SWATMOD-Prep Setup

SWATMOD-Prep is a graphical user interface (Bailey et al. 2017), that was used to set up coupled SWAT-MODFLOW models for the catchments of Gilgelabay (upper part), Gumara, and Ribb (upper part) river that are part of the Lake Tana Basin. Each catchment was discretized into finite different MODFLOW grid cells with a lateral dimension of 210 m by 210 m. The boundaries of the catchments were considered as boundary condition for active and

inactive cells. The rows and columns are oriented east-west and north-south, respectively. The three catchments have a different number of rows and columns as their sizes vary. After the MODFLOW grid cells are created, HRUs are disaggregated into DHRU that are individual, contiguous areas within a sub-basin to allow HRU calculations to be geolocated (Bailey et al. 2017). The DHRUs and the MODFLOW grid cells were intersected, and river segments were defined using polygons (called river cells) that were identified to pass data between SWAT and MODFLOW. Then, SWAT-MODFLOW linkage files were written using subroutines of a three dimensional finite difference subsurface flow model (MODFLOW-NWT) and subroutines from SWAT (2012, Revision 664) to relate HRUs to MODFLOW grid cells and MODFLOW river cells to SWAT stream channels (Bailey et al. 2016; Bailey et al. 2017). MODFLOW-NWT was designed to simulate 3D subsurface flow such as GW recharge, GW discharge, pumping, and interaction of GW-SW with the stream network (Harbaugh 2005). MODFLOW models were created within the SWATMOD-Prep environment using the 30 m resolution SRTM-DEM, aquifer thickness, GW head, hydraulic conductivities, specific storage and specific yield (standard values were assigned based on geologic formations), and river bed material K value. In this study, only the first unconfined layer of the aquifer system was considered due to the limitation of SWAT-MODFLOW in modeling the aquifer system below the first layer (Bailey et al. 2016). In the SWAT model, the first unconfined layer of the aquifer system was assumed to be a layer right above the impervious layer (maximum 6 meter below the surface) to the water table (Neitsch et al. 2011). The geologic log information from 36 drilled wells (AWWCE 2016) were used to determine the water table depth to the impervious layer. The values vary between 0.5 to 12.5 m. We considered the average of the geologic log information (6 m) as the average aquifer thickness in SWAT. The hydraulic head values from the 36 boreholes were used as the initial conditions to simulate aquifer head values for each MODFLOW grid cell under transient condition. Chebud and Melesse (2009) had used the same



kind of data for their MODFLOW modelling work in the Gumara catchment. Recharge data from each HRU were taken directly from the calibrated SWAT model. Finally, SWAT-MODFLOW simulations were carried out for the three catchments, and the spatial and temporal interactions of GW and SW were evaluated for the three catchments. The River package of MODFLOW was used to simulate the GW–SW interaction and the Darcy-equation was used to calculate the volumetric flow of water through the cross-sectional flow area between the aquifer and the stream channel (Bailey et al. 2016). Due to lack of documented information on water withdrawal, pumping rates were not considered in the current study.

#### 4.2.4. Simulation outputs

The model is capable to simulate the hydraulic head for each MODFLOW grid cell, deep percolation (called recharge in SWAT-MODFLOW) for each HRU, volumetric exchange rates ( $\text{m}^3/\text{day}$ ) between the stream network and the aquifer for each SWAT sub-basin and volumetric exchange rate ( $\text{m}^3/\text{day}$ ) between the stream network and the aquifer for each MODFLOW River cell. Our simulations for GW-SW interaction were carried out on a daily time step from 1985 to 2014 and the analyses focused on the monthly hydraulic head, GW-SW exchange, and GW recharge. These outputs were extracted and processed using different R packages such as readr (Wickham et al. 2017), stringr (Wickham 2018), dplyr (Wickman et al. 2018), and ggplot2 (Wickham 2011). Spatial distributions were produced by mapping the model output to the HRU location. These maps presented the spatial extent of source and sink areas, the variation of the hydraulic head, and GW recharge to MODFLOW. Moreover, temporal variations of GW-SW interactions were shown with the help of time series plots for those sub-basins that include gauging stations.

#### 4.2.5. Model evaluation

To evaluate the performances of the coupled SWAT-MODFLOW models for the three catchments, the simulated streamflow data were validated against the measured streamflow

data on monthly basis (Gilgelabay: from 1998 to 2011, Gumara: from 1996 to 2014, and Ribb: from 1998 to 2014). Various statistics like the Nash-Sutcliffe efficiency (NSE), (KGE) Kling-Gupta Efficiency, Coefficient of determination ( $R^2$ ), percent bias (PBIAS), and standardized root mean square error (RSR) are used to evaluate the goodness-of-fit of the hydrologic models. Moreover, the mean hydraulic head was validated using observed hydraulic head values recorded at 36 boreholes during the course of drilling and pump testing (AWWCE 2016).

#### **4.3. Results and discussion**

The models sufficiently reproduced the measured monthly time-series of streamflow. Figure 2 shows a good agreement between the measured and simulated monthly streamflow for the entire simulation periods in the three catchments. Only some peak flow events show smaller deviations. Deviations could result from the coarse spatial representation of rainfall in the input data. In addition, the under estimation of peak flows may be attributed to the SCS-curve number method used in the SWAT model, which does not consider the duration and intensity of rainfall (Tigabu et al. 2019). For all the three catchments, the statistical values of validation periods for streamflow indicated a good (Moriassi et al. 2007) performance (Table 1). Moreover, the model efficiencies in simulating hydraulic head values were very good for Gilgelabay and Ribb catchments, whereas for the case of the Gumara catchment the statistical values were lower (Table 1). It has to be noted that the statistical values computed for the hydraulic head are influenced by the fact that the mean simulated value for the entire modelling period was compared to an observed value measured at one specific day. It is required to install monitoring wells in the studied catchments to further reduced model uncertainty.

Table 4-1: Summary statistics of SWAT-MODFLOW validation for simulated monthly streamflow and mean hydraulic head against the observed ones for the three catchments with respect to different objective functions

Obj.	Gilgelabay		Gumara		Ribb	
function	Streamflow	Hydraulic head	Streamflow	Hydraulic head	Streamflow	Hydraulic head
NSE	0.89	0.87	0.78	0.46	0.89	0.99
KGE	0.81	0.93	0.69	0.48	0.77	0.99
R <sup>2</sup>	0.81	0.88	0.81	0.79	0.90	0.99
PBIAS	2.91	-0.16	22.0	6.3	13.72	-0.49
RSR	0.44	0.36	0.47	0.73	0.34	0.08

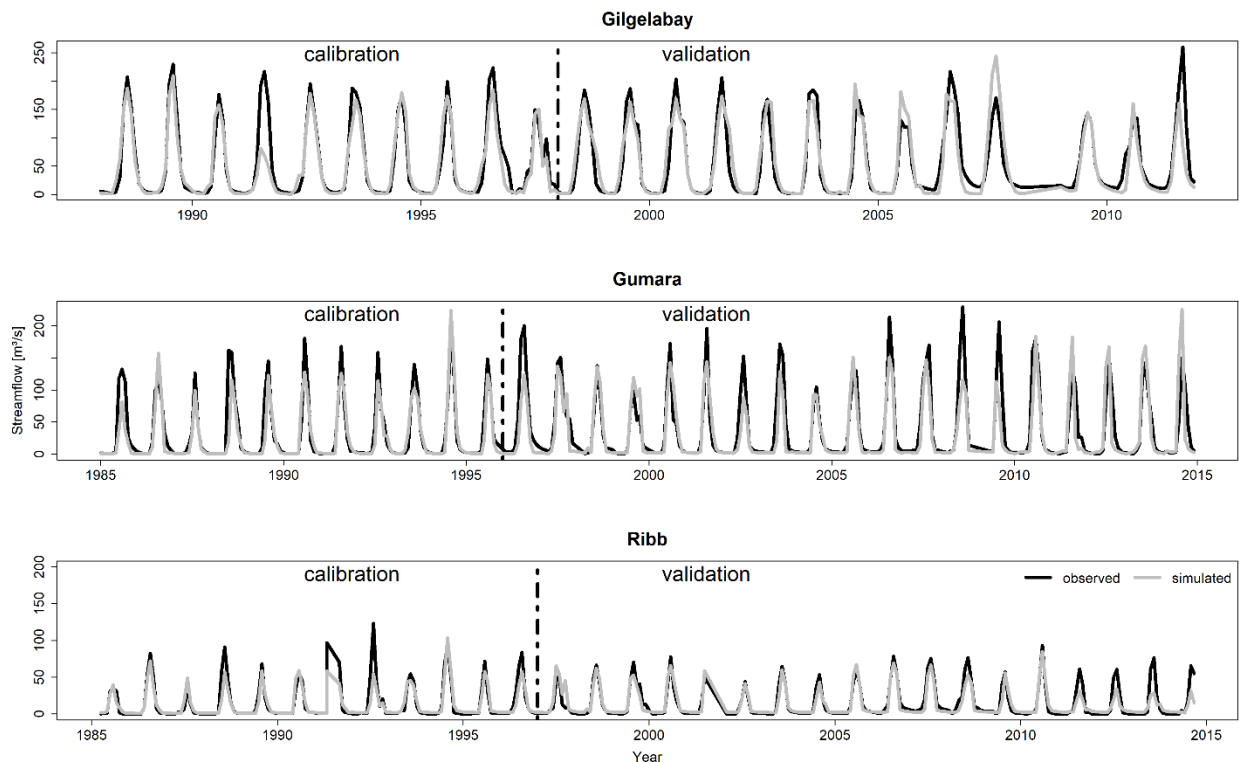


Figure 4-2: Monthly hydrographs showing the SWAT-MODFLOW simulated streamflow against observed streamflow of Gilgelabay, Gumara, and Ribb.

#### 4.3.1. GW-SW interaction

In this study, we identified source and sink areas of aquifer and stream systems. The GW-SW interactions within the three catchments vary spatially and temporally throughout the simulation period of January 1985 to December 2014. This is demonstrated by the volumetric

exchange rate ( $\text{m}^3/\text{day}$ ) between the stream network and the aquifer for each MODFLOW river cell, and between the stream network and the aquifer for each SWAT sub-basin (Fig. 3, 4, and 5). In the highland areas, the stream systems are mainly a source for the aquifer indicating that water is flowing from the river cell to the aquifer, and that the aquifer is a sink for the stream system. The spatio-temporal variations in the GW-SW exchange rates depend on the head difference between the aquifer and the stream and on the aquifer properties such as hydraulic conductivity, specific storage and initial groundwater head (Kim et al. 2008).

In the Gilgelabay catchment, the long-term mean annual volumetric GW exchange rate for each of the SWAT sub-basins is positive indicating that the aquifer system is a source area for the streams systems. The net annual mean contribution from the aquifer to the stream network in the sub-basin at the catchment outlet is  $170 \text{ m}^3/\text{day}$ . However, the flow patterns are highly dynamic on a monthly basis (Fig. 3). The time-series pattern of GW-SW interaction show higher exchange rates during the wet months (July, August, September) and gradually diminish for the rest of the months, which signifies the seasonal variations of aquifer heads. Kim et al. (2008) found similar results to the Musimcheon Basin in Korea when they applied the integrated SWAT-MODFLOW model to simulate spatio-temporal distribution of GW recharge rates and GW evapotranspiration. Both, an exchange of water from the river network to the aquifer and vice-versa can be observed. The latter especially occurs during rainy days indicating that the water level of the stream systems respond fast. Similar study conducted in Pateira de Fermentelos, Portugal proved that the surface water level changes fast in response of aquifer discharge during rainy months (Sena and Condesso de Melo 2012). This might also result from a large variation in the total daily rainfall (Hassan et al. 2014). Moreover, the magnitude of the exchange rate varies from dry season to wet season and depends on the geographic location. During the wet season the mean contribution of the aquifer to the stream network is about  $390 \text{ m}^3/\text{day}$ , whereas the dry season contribution is  $60 \text{ m}^3/\text{day}$ . The lowland

sub-basins showed strong dynamics of GW-SW exchange especially in the rainy seasons, whereas in the highland sub-basins the prevailing flow direction is mainly from the GW to the channel. The annual mean exchange rate is positive for each SWAT sub-basin and negative for each MODFLOW river cell indicating that water is leaving the aquifer to the stream channel. The GW-SW flow resembles some features of the observed streamflow measured at the outlet point of the Gilgelabay catchment (Fig. 4).

In contrast to Gilgelabay, the mean annual volumetric GW-SW exchange rates between the stream network system and the aquifer for each SWAT sub-basin of Gumara and Ribb are not unidirectional. The aquifer system in the Gumara catchment is mainly controlled by the surrounding SW system. However, the flow system at the downstream reaches (sub-basin at catchment outlet) which is found in the floodplain area ( $34 \text{ km}^2$ ), is from the aquifer to the river network system (Fig. 5). This indicates that the floodplain is serving as a storage area for both surface and groundwater. Our result confirms the findings of Dessie et al. (2014) who reported that the floodplain of Gumara catchment were recharged by the groundwater during the rainy season. Chebud and Melesse (2009) also reported that 0.09 billion cubic meter of water flows out from the Gumara floodplain aquifer to the Lake Tana during the wet season. Besides the downstream reaches (floodplain area), there are a few sub-basins from middle and upstream part of Gumara catchment that the flow system is from the aquifer to the stream network (Fig. 5). The mean annual GW-SW interaction rate of the Gumara catchment at its outlet showed that the aquifer system was gaining a significant amount of water from the stream before the year 1994, and the flow magnitude gradually decreased afterwards (Fig. 4). This decrease of the flow magnitude of water from the river network to the aquifer over time could be related to the increase of runoff, which has been reported by Tigabu et al. (2018), and less seepage of water from the stream. Likewise, the flow dynamics of the Ribb catchment are mainly controlled by the surrounding SW system for the period before 1990, whereas after 1990 the

flow direction was changed from the aquifer to the stream network system (Fig. 4). This might be due to a change in the number of rainy days and rainfall duration and intensity (Teshome 2016). As the total rainfall amount did not change significantly, the rainfall became more intense and its duration became shorter which very likely results in more surface runoff generation and less seepage to the aquifer system. This is one reason for the fact that the stream systems are perennial. Moreover, the simulation indicates that the magnitude and direction of daily GW-SW interaction is more variable than the annual values (Figure 3). The prevailing flow direction is from the stream network to the aquifer system. The strong dynamics of the daily GW-SW interaction could be related to the large variations in the water table during a hydrologic year, whereas the changes in the flow domain may be attributed to the variation in topography and rainfall. The large variation in the water table during the year indicates that a stream segment could receive water from groundwater for a portion of the year and lose water to groundwater at other times (Figures 4 and 5). A comprehensive discussion was given by (Sophocleous 2002) on how GW-SW exchange rate and flow direction vary with rainfall and hydraulic head.

The spatio-temporal variations of the GW-SW interactions among the three catchments could be linked to the heterogeneity of the catchments with respect to topography, soil, geology, as well as to the seasonal variations and the temporal pattern of the rainfall in each catchment. The magnitude of GW-SW interaction is highest during the rainy (summer) season compared to other seasons. The high degree of variability on the daily and seasonal GW-SW exchange rates might be attributed to a large variation in daily rainfall (coefficient of variation ranging from 100 to 200%). Moreover, the GW-SW exchange rate between the stream network and the aquifer for each SWAT sub-basin varies spatially within each catchment and between the catchments (Figure 6). On the one hand, mean values of GW-SW exchange rates are primarily positive for Gilgelabay catchment with a daily discharge values from the aquifer system

ranging from 1 to 2000000 ( $\text{m}^3/\text{day}$ ) per sub-basin, whereas seepage values from the river network system to the aquifer vary between 2050 and 124 000  $\text{m}^3/\text{day}$  per sub-basin, indicating that discharge from the aquifer system is higher than the seepage from the stream network system. On the other hand, the mean values of GW-SW exchange rates for Gumara and Ribb catchments are mainly negative, i.e. seepage from the stream network is greater than the discharge from the aquifer system. This indicates that there are differences in the GW-SW interaction between the three catchments and within each catchment. Overall, the GW-SW interaction in the Gilgelabay catchment differs from the catchments of Gumara and Ribb catchments due to the differences in the hydraulic conductivity, specific storage, and specific yield values assigned based on the soil distribution as well as to the difference in the rainfall, river gradient, and hydraulic head. For instance, in Gilgelabay catchment the hydraulic conductivity values vary between 0.1 to 0.35  $\text{m}/\text{day}$  and the specific yield varies from 10% to 18%, whereas in Gumara and Ribb the hydraulic conductivity values are between 0.1 to 1.25  $\text{m}/\text{day}$ , and the specific yield varies from 12% to 28%. These relatively smaller hydraulic conductivity and specific yield values in Gilgelabay catchment caused smaller GW-SW interaction rate compared to Gumara and Ribb catchments.

In general, from the above analyses one can certainly conclude that the GW-SW system in the study area are hydraulically connected, and the GW-SW interactions differ from between the three catchments.

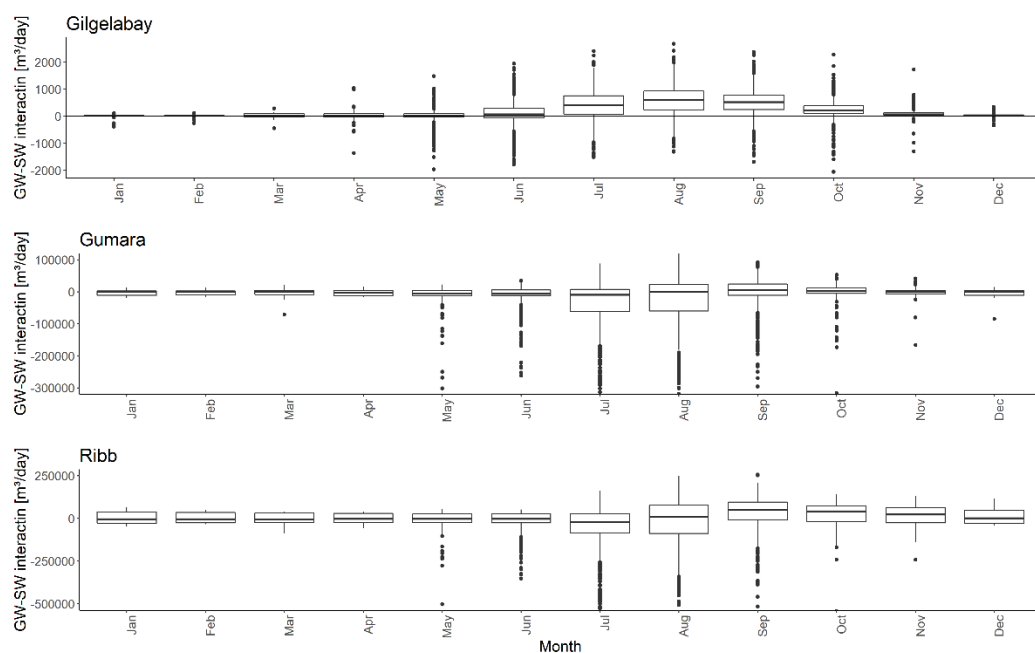


Figure 4-3: Seasonal variation of GW-SW exchange rate for Gilgelabay, Gumara, and Ribb catchments for the river cells at the outlet of each catchment.

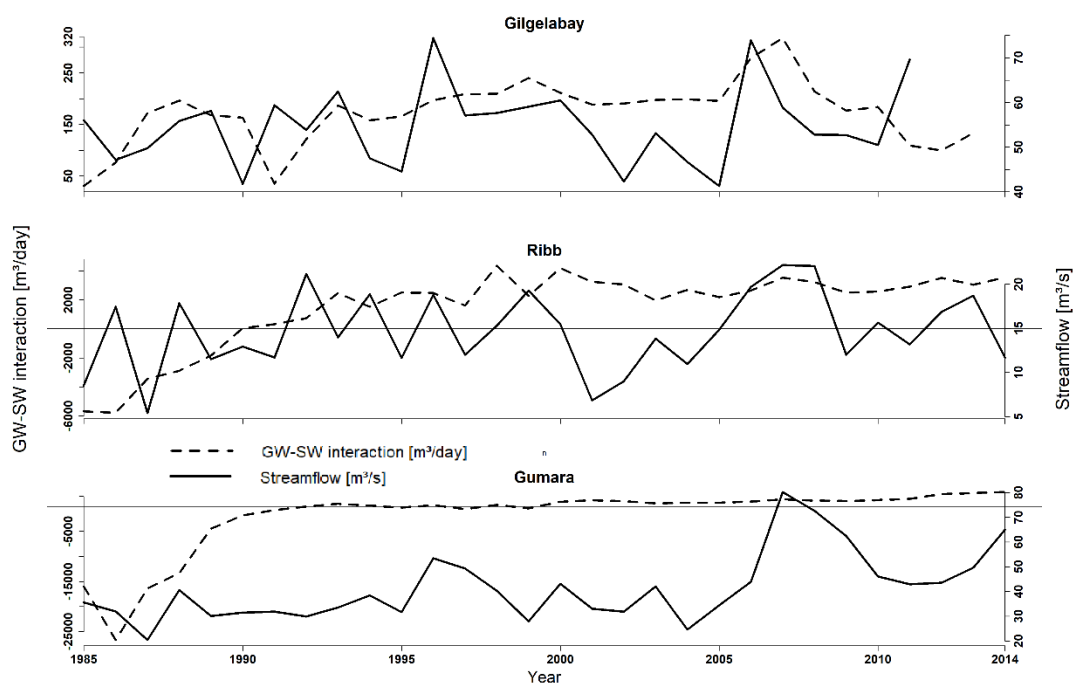


Figure 4-4: Temporal variation of the GW-SW interaction rate (m³/day) between the aquifer system and outlet SWAT sub-basins against measured streamflow for Gilgelabay, Gumara, and Ribb catchments.



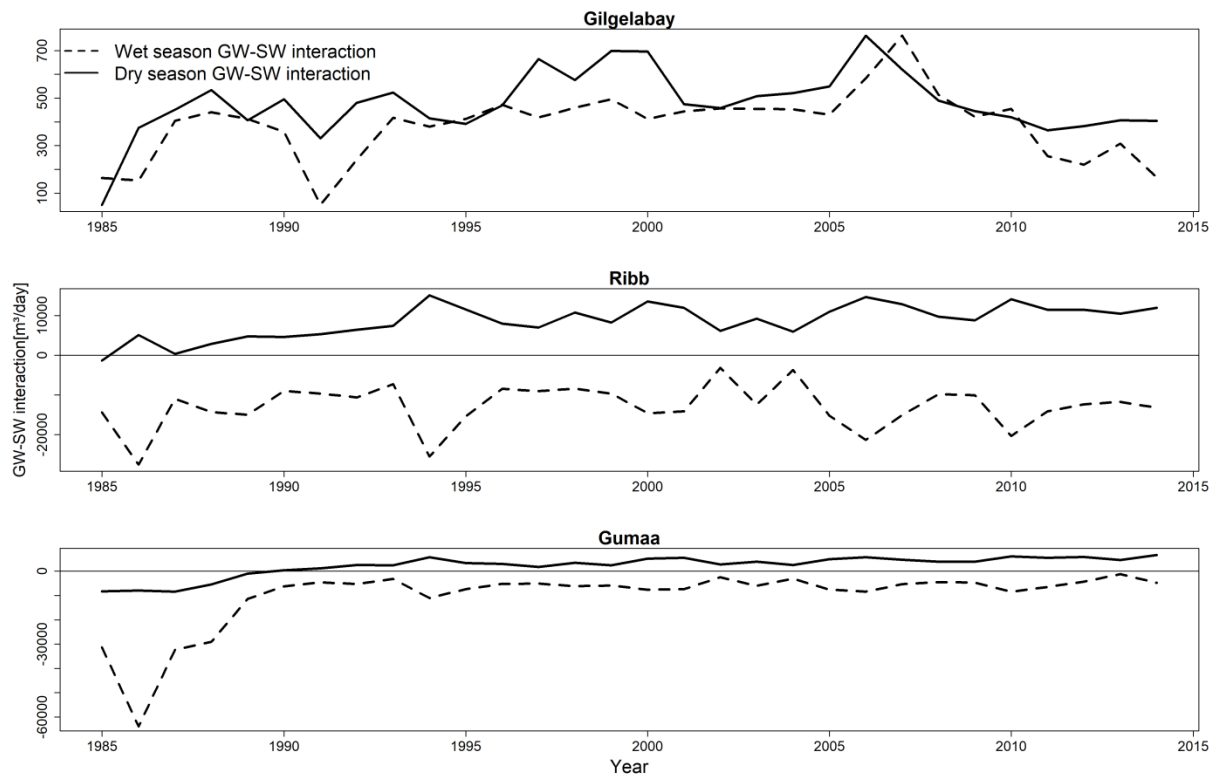


Figure 4-5: Variation of the GW-SW interaction rate (m<sup>3</sup>/day) between the aquifer system and outlet SWAT sub-basins during the wet and dry seasons for Gilgelabay, Ribb, and Gumara catchments. Positive values indicate groundwater discharge to the stream system, whereas negative values indicate seepage from the stream network to the aquifer.

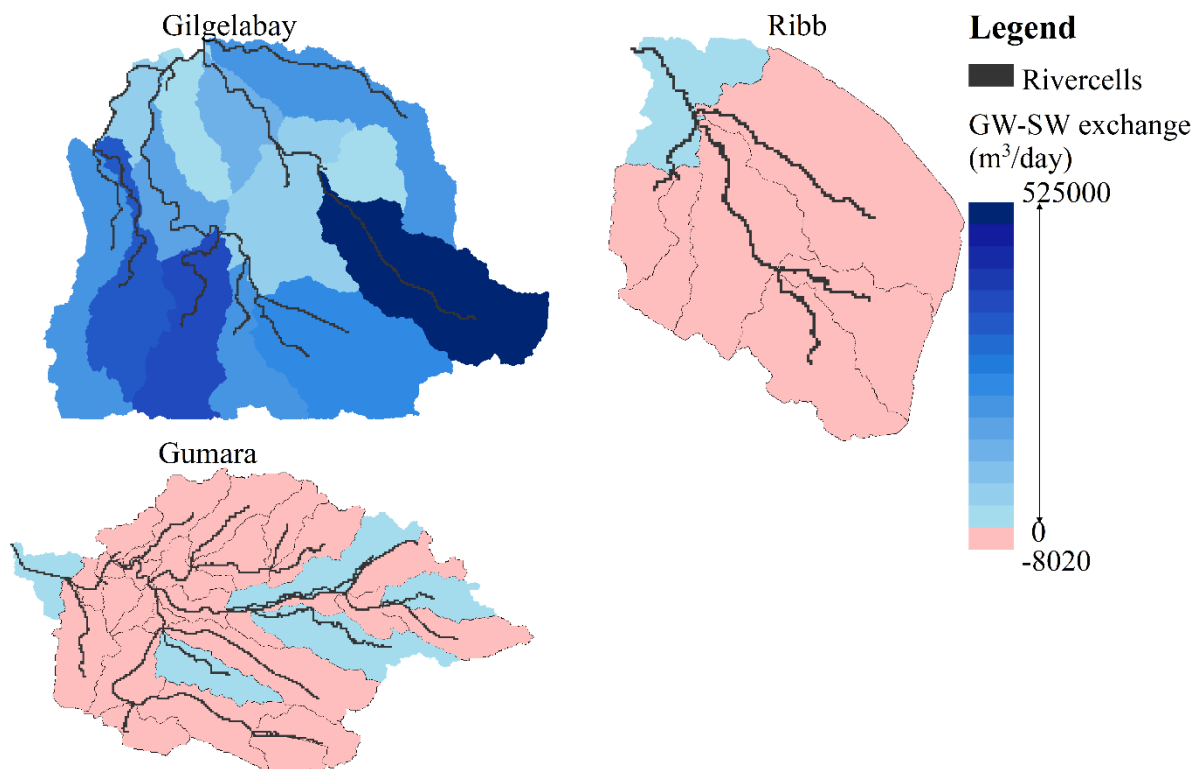


Figure 4-6: The volumetric GW-SW interaction rate (m<sup>3</sup>/s) between SWAT sub-basins and stream network systems. Positive values indicate groundwater discharge to the stream system, whereas negative values indicate seepage from the stream network to the aquifer.

#### 4.3.2. Recharge

The coupled SWAT-MODFLOW model simulates the amount of recharge in mm to MODFLOW for each HRU (called deep percolation in SWAT-MODFLOW) and the volumetric flow rate of recharge (m<sup>3</sup>/day) to each MODFLOW grid cell. The average monthly deep percolation (mm) during the period 1985–2014 varies from 0 to 90, 0 to 75, and from 0 to 60 in the Gilgelaabay, Gumara, and Ribb catchment, respectively. The volumetric flow rate of recharge (m<sup>3</sup>/day) provided to each MODFLOW grid cell shows the spatial variation of recharge to the aquifer (Figure 7). Higher recharge rates correspond to the highland areas and low recharge rates are associated with the lowland areas. This is due to the fact that most of the time highland areas have groundwater heads below stream stage and lowland areas have groundwater heads above stream stage. Bailey et al. (2016) also found higher recharge rates in the highland areas of the Sprague River Watershed in southern Oregon, USA, by applying the same model. Simulated cell-wise annual average recharge rates provided to each MODFLOW grid cell range from 10 – 140 m<sup>3</sup>/day in the Gilgelaabay catchment, from 6 – 105 m<sup>3</sup>/day in the Gumara catchment, and from 4 – 90 m<sup>3</sup>/day in the Ribb catchment (Figure 7). Additionally, there are considerable differences between the wet and dry season recharge rates. The vast majority (75 to 91%) of recharge takes place during the wet (summer) season as the main source of recharge to the groundwater system is rainfall. Whereas only 9 to 25% occur during the dry season. This indicates that the regional groundwater flow system is seasonally limited. The current result is in agreement with the result of Woldeamlak et al. (2007) for the Grote-Nete catchment, Belgium that got 86% of its recharge during the wetter (winter) season (but different climatic zone). The recharge areas are mainly associated with the highland areas and with areas dominated by soils with a coarse texture like Eutric Leptosols and Eutric Regosols. GW

discharge areas mainly correspond to the stream network and floodplains, which is in agreement with Searl et al. (1999). Aquifer systems of such a type (GW discharge areas) are mainly recharged locally and depends on the amount of rainfall, evaporation and temperature. However, at times of high river flows (wet season), water moves from the stream system into the groundwater system. This is clearly revealed by the GW-SW interactions between the SWAT sub-basins and stream network systems during the wet and dry seasons (Figure 5).

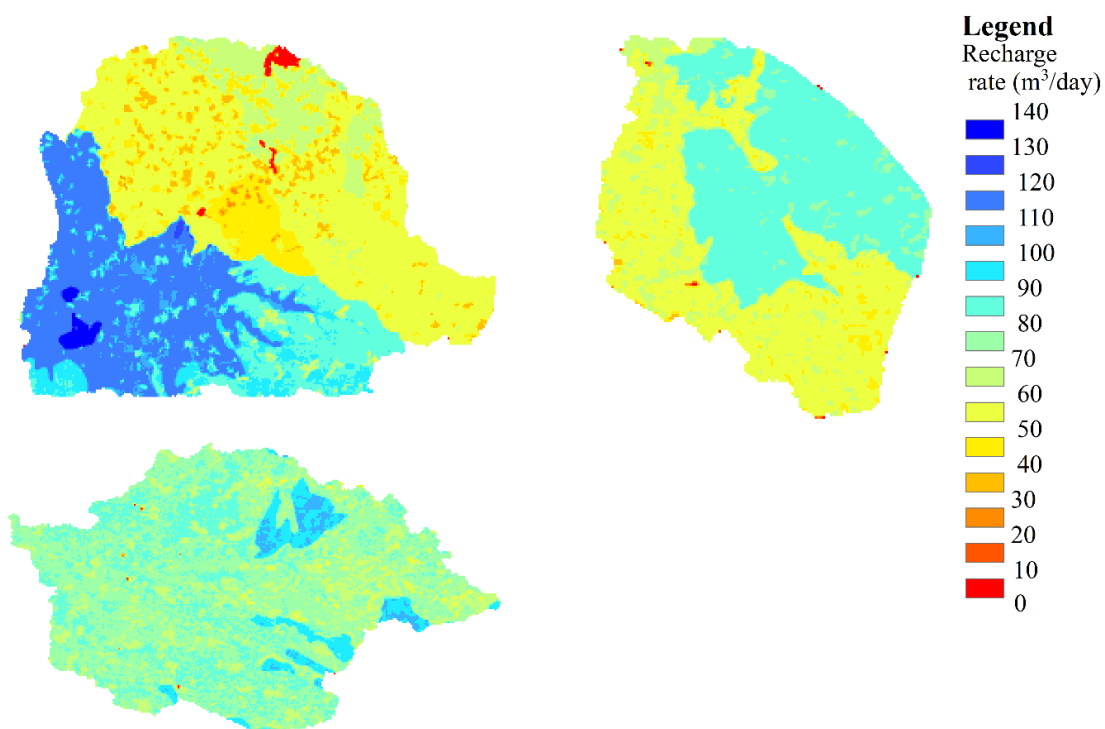


Figure 4-7: The volumetric groundwater recharge rate (m<sup>3</sup>/day) to the water table of MODFLOW grid cells in Gilgelabay (top left), Gumara (bottom left) and Ribb (top right) catchments.

#### 4.3.3. Hydraulic head

In hydraulically connected GW-SW systems, the aquifer head is an important variable that controls the resulting exchange between the stream network and the aquifer system. The main driving force of GW flow is the hydraulic potential that mimics the topography in the case of unconfined aquifers (Fan et al. 2007). The flow to and from the aquifer is a function of the difference between the river stage and the aquifer hydraulic head. Simulated mean daily

hydraulic head values for the given modelling period are shown in (Figure 8). Both the highest (3640 m) and the lowest (1783 m) hydraulic head values were estimated for Gumara catchment (Figure 8). The temporal hydraulic head differences for MODFLOW grid cells at the outlets for dry and wet seasons vary between 1 and 2 m. The hydraulic head values show a similar pattern as the topography for all the three catchments indicating that the shape of the water tablet is highly influenced by topography. This is in agreement with research findings of Sena and Condesso de Melo (2012), who produced a water table map from water table and surface water level data measured in the field and reached to the conclusion that the shape of the water table maps were greatly influenced by the topography and the streams. The depth from the ground surface to the water table varies between 1 and 30 m in case of Gilgelabay and from 1 to 15 m for Gumara and Ribb. It is shallow in the lowlands (1 to 2 m and deeper in the highlands and at the water divides ranging from 1- 30 m.

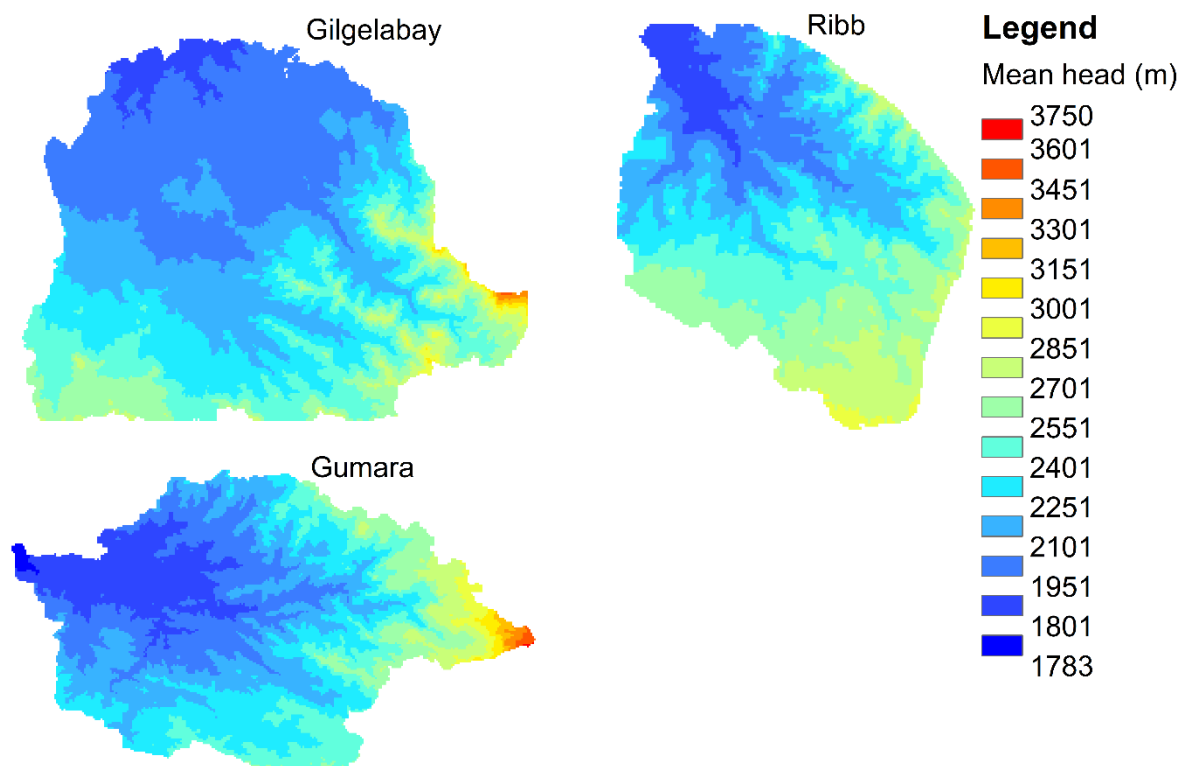


Figure 4-8: Spatially varying long-term mean hydraulic head values of Gilgelabay (top left), Ribb (top right) and Gumra (bottom left) catchments as simulated using the SWAT-MODFLOW model.

#### 4.3.4. Implications for water resources management

As the Lake Tana basin is considered as one of the development corridor sites by the Government of Ethiopia, understanding GW-SW water interaction and implementing combined use of GW and SW is the top priority for water managers to contribute to a sustainable development in the region. The present study focuses on the investigation of GW-SW interaction of three catchments in the Lake Tana basin. Our findings provide insights for water managers and policy makers for future planning. We found that GW and SW are hydraulically connected and the stream network systems are dominated by GW flow in Gilgelabay catchment and vice-versa in Gumara and Ribb catchments. Thus, sustainable water resources management will be achieved if the future water resource development plan puts a particular focus on the combined use of groundwater and surface water. The hydraulic head and GW-SW interaction showed considerable spatial and seasonal variations in all the three catchments. In Gumara and Ribb catchments, the wet season flow pattern is dominantly from the river to the aquifer system, whereas the dry season flow is to the river system. This implies that GW and SW withdrawal e.g. for drinking water use affect this interaction differently in the wet and dry season. Spatial patterns of the hydraulic head should be considered to define GW recharge and discharge zones prior to water withdrawal from the aquifer system. Moreover, understanding the GW-SW interaction is important to characterize the general ecosystem status as the streamflow in all the three catchments are connected to the GW. Hence GW is critical with regard to water availability as well as with regard to the control of environmental flow.

#### 4.4. Summary and conclusions

The aim of this study was to investigate GW-SW flow dynamics in the Lake Tana basin by considering three catchments as case studies (Gilgelabay, Gumara and Ribb) using the coupled SWAT-MODFLOW model. Results from this study indicated that SWAT-MODFLOW can simulate the surface and subsurface hydrologic processes in the study areas and can provide

insights into GW-SW interactions. The capability of the model to produce reliable results was reflected by the good match of the simulated and observed streamflow data as well as by the comparison between observed hydraulic head values measured at water wells during the course of drilling and mean simulated hydraulic head values. The key findings of this study are:

1. The aquifer and the stream network systems are hydraulically connected in all catchments in both wet and dry seasons. This was proven by the simulated volumetric GW-SW exchange rates between each SWAT sub-basin (aquifer) and stream network, and the stream network and the aquifer for each MODFLOW river cell. The majority of the flow is from the aquifer to the stream network system particularly in Gilgelabay catchment.
2. In all catchments, the groundwater and surface water flow system is more variable on the daily time scale than on the monthly time scale. This was shown by the simulated results of GW-SW exchange rates, water recharge to the groundwater table and discharge from the aquifer system.
3. Despite the fact that daily GW-SW exchange rates are highly variable in the Gilgelabay catchment, the annual volumetric exchange is from the aquifer system to the stream network system indicating that stream systems are gaining.
4. In both Gumara and Ribb catchments, the annual volumetric GW-SW exchange rates are more dynamic in time compared to Gilgelabay catchment. This was suggested by the GW-SW exchange rates between each SWAT sub-basin and stream network systems (Fig. 5 and 6). During the wet seasons, the flows dominantly from the stream system to the aquifer, while it is from the aquifer to the stream network system during the dry season.
5. The annual GW-SW exchange rates at the outlet sub-basins show a change in the flow direction of water for Gumara and Ribb after 1995 and 1991, respectively (Fig. 4).

Before the mentioned years, the flow system was from the stream network to the aquifer system and after these years the flow direction changed from the aquifer system to the stream network. This might be related to the decline with the number of rainy days (specially the dry season) since 1990 while the total annual rainfall was not significantly changed.

6. The modelling results have been checked for their reliability using measured and simulated streamflow time series and hydraulic head values measured during the drilling of wells. However, the model could be improved if regularly measured time series of water table elevation and stream stage values were available.
7. This study primarily focuses on the setup of a coupled SW and GW model to understand the hydrodynamic condition of the GW-SW system in the study area. The model is valuable because it can be used to assess climate change impacts on groundwater resources in the future.

## **5. Climate change impacts on the water and groundwater resources of the Lake Tana Basin, Ethiopia**

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## **Abstract**

Climate change causes strong impacts on water resources. In particular, the mid- to long-term effect on groundwater will be challenging in many regions, which rely on groundwater to meet their water demands. This is the case in the Lake Tana basin, Ethiopia, where discharge regimes are dominated by base flow from the shallow aquifer. The Lake Tana basin has more than three million inhabitants and the required water is largely extracted from groundwater. Therefore, the potential impact of climate change on the major water balance components has been assessed in the Lake Tana basin for two future periods: mid-term (2031-2060) and long-term (2065-2094) assuming that anticipated changes of temperature and rainfall would cause substantial impact on major hydrological components. We focus on changes in the groundwater contribution to stream flow (GWQ) and other major water balance components (actual evapotranspiration, surface runoff, and water yield) in two tributary catchments (Gumara and Gilgelabay) of the Lake Tana basin. The hydrologic model SWAT was used to assess likely changes under two representative concentration pathways (RCP4.5 and 8.5). Under the utilized RCPs, average temperature is expected to increase by 2.2°C and 3.6°C for the mid-term and long-term of the century, respectively. We used a total of 35 bias corrected regional climate models (RCMs) from the CORDEX dataset for both catchments. Compared to the baseline average, outcomes of this research revealed that the groundwater contribution to stream flow is projected to decrease whereas surface runoff is projected to increase. No or only slight changes in rainfall are expected, but the number of days with rainfall is expected to decrease in both catchments under the two concentration pathways. In conclusion, these results could have considerable advantages for the future water resource management and planning in the basin and other similar regions expecting significance warming.

Keywords: Climate change, groundwater, water balance, surface runoff, SWAT, Ethiopia.

## 5.1. Introduction

Climate change causes strong impacts on the natural systems on all continents (Field et al. 2014). The water cycle is highly affected by climate change. There are many evidences that show impact of climate change on different components of the hydrologic cycle across the globe. According to (Marx et al. 2018), half of the rivers in Europe will experience decreases in the low flow (7% - 12%) under 1.5 K warming for the period 2047-2076. A review paper by Meixner et al. (2016) in US reported likely declines in the recharge of aquifers in the western US during the end of the 21st century. Under RCP4.5, Ndhlovu and Woyessa (2020) found a slight decrease (1%) in the annual rainfall, whereas water yield and runoff will increase by 5% and 6%, respectively for the period of 2020–2050 in the Zambezi River Basin, Africa. Gebremeskel and Kebedeb (2018) reported 13% and 14% declines of surface runoff under A1B and B1 scenarios, respectively for the period 2015-2050 in Werii watershed of the Tekeze River, Ethiopia. The annual mean soil moisture is also anticipated to decrease in most subtropical regions (IPCC 2014). Consequently, uncertainties associated with future water resources management are growing due to the effect of climate change (Abbaspour et al. 2015). To minimize uncertainties associated with future water management plans and to secure the future water needs of the global community, many efforts have been made in investigating the impact of climate change on water resources across the planet. However, the majority of the studies focuses more on surface water bodies than on groundwater (Meixner et al. 2016; Saha et al. 2017), and African countries are underrepresented in these efforts (Field et al. 2014). It is well known that the social-ecological systems of developing countries are severely impacted by climate change due to the lowest capacity to adapt (Dille et al. 2018). This indicates that more efforts are required to investigate the effect of climate change in developing countries like Ethiopia.

Compared to surface water, groundwater is a reliable and cost-effective resource especially in many African countries and other parts of the world where availability of surface water is limited (Bovolo et al. 2009). One third of the global freshwater is extracted from the groundwater source (Taylor et al. 2013). In Ethiopia, groundwater provides 80% of the national water demand (Kebede 2018). This national condition is the same in the Lake Tana basin.

In the Lake Tana basin, being a home for more than three million people and a head water source of the Blue Nile River, several studies were carried out to investigate the impact of climate change on its hydrology. Nevertheless, the vast majority of the climate change studies were focused on streamflow or runoff analyses and there are disagreements in their findings (Abdo et al. 2009; Taye et al. 2011; Dile et al. 2013). Abdo et al. (2009) and Dile et al. (2013) studied the hydrologic responses of Gilgelabay catchment under climate change. According to Dile et al. (2013), the monthly mean volume of runoff in Gilgelabay catchment tends to increase significantly (up to 135%) for the mid and long-term of the 21st century. Contrary to Dile et al. (2013), Abdo et al. (2009) reported decreases in the monthly mean runoff in the same catchment. Taye et al. (2011) also studied the future development of streamflow in the Lake Tana basin under climate change. In this study, both increases and decreases (-75% to 81%) of streamflow are expected during 2050s in different catchments in Upper Blue Nile Basin. Groundwater contributes a substantial amount of water to the flow of streams in the Lake Tana basin. Even though it has a significant contribution to the streamflow (Setegn et al. 2008; Tigabu et al. 2019), all past studies ignored it in their analyses. The only studies that addressed multiple water balance components and groundwater flow analyses under climate change in the Lake Tana basin are Setegn et al. (2011) and Woldeesenbet et al. (2018). Setegn et al. (2011) analysed the responses of streamflow, actual evapotranspiration, soil moisture, and groundwater

contribution to the streamflow based on 17 GCM outputs from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3). Their results indicated that the annual streamflow tends to decline significantly for most of the GCMs considered for the study, while the actual evapotranspiration is expected to increase. A likely decrease of groundwater flow and soil moisture was reported. However, the magnitudes of changes in the groundwater flow as well as the spatial patterns of changes were not considered. Woldesenbet et al. (2018) also studied the impacts of future climate change on the hydrological components of the Lake Tana Basin under RCP6.0. Their results showed that the groundwater contribution to the streamflow, percolation, and actual evapotranspiration would increase on the annual time scale, but decreases are expected during the small rainy season compared to their reference period (1980-2005). Although this research is comprehensive in addressing the major water balance components, it does not address the impact of climate change on the major hydrological components during the mid-term and long-term of the 21st century as the authors focused only on a short-term period (2016–2030). In addition, high level concentration pathways were not considered. Thus, the main purpose of this study is to enhance our understanding of how projected changes in rainfall and temperature will affect the groundwater contribution to the streamflow and other major water balance components in Gilgelabay and Gumara catchments, which are the two major tributaries of Lake Tana during the mid-term (2031-2060) and long-term (2065-2094). The specific objectives are i) to assess if groundwater contribution to the streamflow and other major water balance components have significantly changed in response to climate change and ii) to determine if changes in the groundwater contribution to the streamflow show a distinct spatial pattern in the study area.

## **5.2. Materials and methods**

### **5.2.1. Study area**

The Lake Tana basin is entirely located in the Amhara regional state in the north-western highlands of Ethiopia (Figure 1). It is one of the sub-basins of the Blue Nile River in which the largest fresh water lake in the country is found. The total catchment area of the Lake Tana basin is 15,321 km<sup>2</sup>. More than 40 streams are flowing into Lake Tana (Alemayehu et al. 2010). Among others, Gilgelabay and Gumara contribute about 70% of the inflow to the lake. The Blue Nile (locally referred to as Abay) is the only surface outflow from the lake with an average annual flow volume, as calculated from raw data (1973 to 2014), of 3.9 billion m<sup>3</sup> (123 m<sup>3</sup>/s) measured at the lake outlet.

Similar to its hydrologic variability, the Lake Tana basin has a heterogeneous hydrogeology. According to Kebede et al. (2005), areas surrounding Lake Tana are covered by quaternary basalts and alluvial sediments. These geologic formations are characterized by high groundwater transmissivity that vary 100–700 m<sup>2</sup>/day. The highland part of the basin on the other hand is covered by the basaltic plateau, where the groundwater transmissivity is lower compared to the quaternary basalt and sediments (Kebede et al. 2005). Being driven by the diversified parent geology, the soil structure, lateral and vertical extents, and hydraulic conductivity the basin is highly diversified. The soils vary from hydrologic group B to group D, which represent infiltration rates from moderate to very slow. Additional information can be found in Tigabu et al. (2019). Gilgelabay and Gumara are the two perennial rivers that are characterised by a succession between bedrock types in their higher reaches, and alluvial types in their lower reaches and floodplains (Poppe et al. 2013). There is a significant topographic variation between the lowland and the mountain ranges. This diversified topographic feature of the catchment and the movement of the inter-tropical convergence zone (ITCZ) result in a spatially varying rainfall pattern in the basin. June to September is the rainy season in the

catchment corresponding to the ITCZ position north of the Equator. The amount of annual rainfall is directly related to elevation above mean sea level: high rainfall is observed in the highlands, whereas low rainfall is measured in the lowlands (Tigabu et al. 2018). Moreover, large (global) atmospheric circulation and sea surface temperatures such as large scale forcing through El Niño Southern Oscillation (ENSO), Quasi-Biennial Oscillation (QBO), as well as west-east sea surface temperature gradients over the equatorial Indian Ocean are significantly influencing rainfall variability (Omondi et al. 2014). The catchments are characterized by intensive agriculture. About 60% of catchments are cultivated land.

#### 5.2.2. Data base

Daily rainfall and minimum and maximum temperature values from 5 meteorological stations for the years 1980 to 2014 were used, which were provided by the National Meteorological Service Agency (NMA 2016). Daily streamflow data of Gilgelabay near Merawi, and Gumara near Bahirdar gauging stations for the years 1980 to 2014 were obtained from the Department of Hydrology, Ministry of Water, Irrigation and Electricity of the Ethiopian Government (MoWIE 2016).

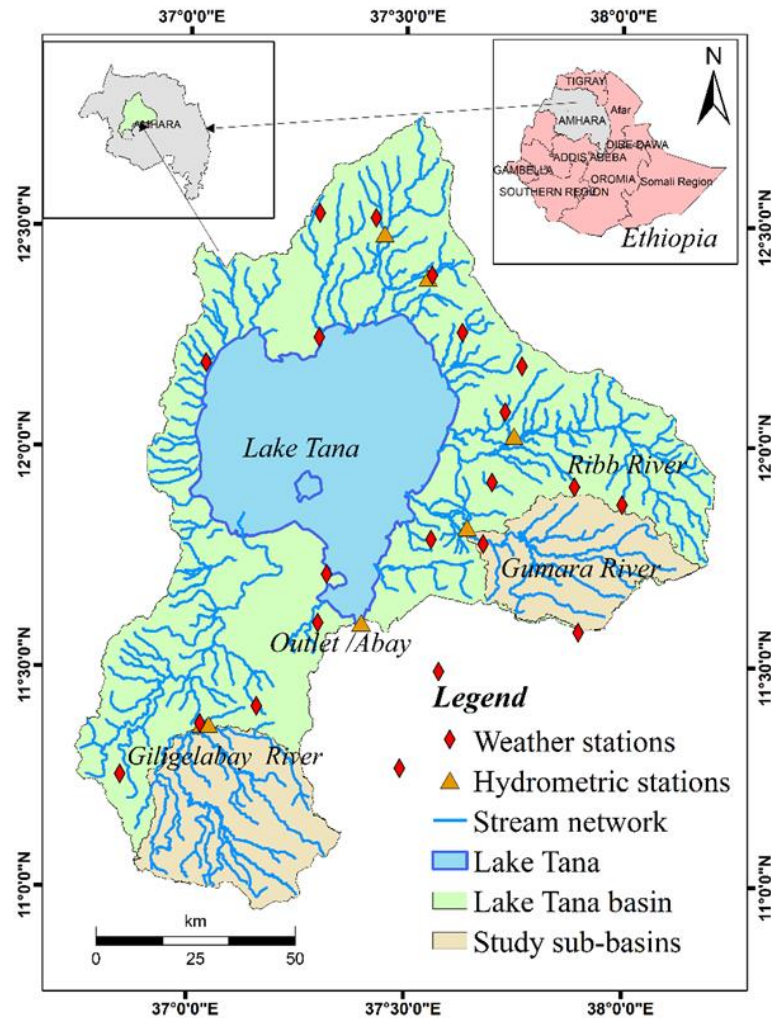


Figure 5-1: Location map and major tributaries of Lake Tana including river gauging and weather stations

### 5.2.3. Hydrological modeling

Numerous hydrological models have been used to study the impact of climate change on water resources. The semi-distributed, continuous eco-hydrological model SWAT (Soil and Water Assessment Tool) (Arnold et al. 1998; Arnold and Fohrer 2005) is widely applied. The model is capable of simulating water balance components based on hydrological response units (HRUs). Groundwater processes are represented by a shallow and a deep aquifer in the model. The shallow aquifer in the SWAT model is defined as an unconfined aquifer that contributes to streamflow in the main channel of the respective sub-basin (Neitsch et al. 2011). The input component to the hydrologic balance equation is rainfall, and is partitioned into actual



evapotranspiration, water entering to the vadose zone, and surface runoff.

In this study, calibrated SWAT models for Gilgelabay and Gumara catchments (Tigabu et al. 2019) were used. The model showed a reasonable performance on the daily time scale ( $NSE > 0.65$ ,  $KGE > 0.62$ ,  $R^2 > 0.8$ ,  $RSR < 0.5$ , and  $PBIAS < 21\%$ , validation period, Moriasi et al. 2007). In addition to statistical indices, the fitness of the models in capturing the monthly streamflow data were also evaluated by comparing the measured and simulated streamflow hydrographs and flow duration curves. The simulated hydrographs and flow duration curves were consistent with the measured ones indicating that the models are capable of simulating hydrologic processes in study catchments. The flow duration curves showed very good agreement for the middle and low flow conditions in both catchments, which are indicative of representing groundwater contribution to streamflow. Hence the model is suitable for assessing the impacts of climate change on groundwater and water resources in the two catchments. Detailed information on the parameters and calibration procedures are available in Tigabu et al. (2019). As the magnitude of groundwater flow in a catchment is counterbalanced by the other hydrologic components, we also analysed ET, SURQ, soil moisture content, and percolation.

#### 5.2.4. Projected climate change data

To assess impacts of future climate change on water resources different emission scenarios as expressed in the representative concentration pathways (RCPs) are used. Global Circulation Models (GCMs) and the Coordinated Regional climate Downscaling Experiment (CORDEX) are the most commonly applied and physically based ways in formulating different climate scenarios (Elshamy et al. 2009). Nevertheless, GCMs are unsuitable for local climate impact studies due to their coarse spatial resolution and incapability to capture local effects (Navarro-Racines et al. 2020). To overcome these limitations, regional climate models (RCMs) are applied to downscale GCM outputs (Eden et al. 2014; Mascaro et al. 2015). CORDEX

coordinates RCMs to improve regional climate downscaling models and techniques and to produce coordinated sets of regional downscaled projections worldwide (Giorgi and Gutowski Jr 2015). There are multiple CORDEX domains worldwide including the CORDEX African domain. Although RCM outputs provide a better spatial and temporal resolution than GCM outputs, projected temperature and rainfall are still biased (Berg et al. 2012). Consequently, a number of bias correction methods are available to overcome this problem. The main adjustment methods are based on the mean, both mean and variance, and quantile values. Among others, linear scaling and local intensity scaling, power transformation method, distribution mapping or quantile mapping are widely applied (Smitha et al. 2018).

Climate models can project future rainfall and temperature. However, there are considerable differences and uncertainties in the projected rainfall among the different climate models (Kling et al. 2012; Kiesel et al. 2019). According to Mascaro et al. (2015), the CORDEX-African RCMs have significant biases among the individual models. For this reason, an ensemble modeling approach that depends on a number of RCMs is required to minimize biases and obtain a representative result (Kling et al. 2012).

Past climate change studies in the Lake Tana basin were mainly based on single GCM (Abdo et al. 2009; Dile et al. 2013; Adem et al. 2016) at the Coupled Model Intercomparison Project (CMIP3) results. However, model outputs from CMIP3 have course spatial resolutions and are not as comprehensive as model outputs from CMIP5 (Taylor et al. 2012). According to Taylor et al. (2012) and Stocker et al. (2013), climate models under CMIP5 are capable to represent bio-geological processes, aerosols and carbon cycles that interact with physical climate. As a result, better simulations are expected under CMIP5 than under CMIP3. Reports by Maher et al. (2017) and Kusunoki and Arakawa (2015) indicated that annual and seasonal rainfall simulated from CMIP5 showed higher reproducibility than CMIP3 over the western Himalayan

and East Asia regions, respectively. Consequently, we used daily rainfall and temperature data of 15 RCMs for RCP4.5 and RCP8.5 (Table 1) from CORDEX Africa which are driven by GCMs in CMIP5 (Mascaro et al. 2015).

#### 5.2.4.1. Bias correction

Climate model data can differ considerably from the measured data. This bias needs to be corrected prior to using climate change scenario data in hydrological impact studies (Berg et al. 2012; Ehret et al. 2012). For this study, we applied five bias correction methods: distribution or quantile mapping (pDM) and linear scaling (pLS) for both rainfall and temperature, and local intensity scaling (pLIS) and power transformation for rainfall (pPT) as well as variance scaling (VS) for temperature data. The bias correction methods were applied based on the measured rainfall and temperature data during 1980-2005, and the seasonal patterns and median values of the climate data before and after bias correction were compared with the observed climate data for the period (1980-2005). Even though the measured climate data were available for the period 1980-2015, the comparison of rainfall outputs from CORDEX with the measured ones was carried out for the period 1980-2005. This is because climate data from GCM-RCMs were free from radiative forcing only before the year 2006 (IPCC 2014).

We selected GCM-RCMs outputs based on the plausibility of the simulated rainfall outputs, as rainfall is the most important input for hydrologic modelling. The following criteria for model selection were applied:

Firstly, we analyzed the GCM-RCM data before any bias correction method was applied. The monthly average rainfall of the climate scenario data (1980 to 2005) was compared to the measured data (Figures 2 & 3). Those GCM-RCM outputs that did not have a bi-modal rainfall pattern were removed. Secondly, five bias correction methods were applied for the climate data outputs that were selected during the first screening step.

Thirdly, the bias corrected climate data were compared with observed rainfall data for each station based on root mean square error computed using long-term mean monthly average values. The RMSE computation was applied for the dry season, wet season, and all months independently to identify a dry/wet bias in the scenario data. Then bias corrected GCM-RCM outputs that showed a RMSE value  $<0.5$  mm/day and represented the seasonality (Figure 4) were selected for climate change impact analysis. The selected general circulation model (GCM) and regional climate model (RCM) combinations, their full names and institutions are given in Table 1. Detailed information about the bias correction methods used for this study are available in Kiesel et al. (2019) and Teutschlein and Seibert (2013).

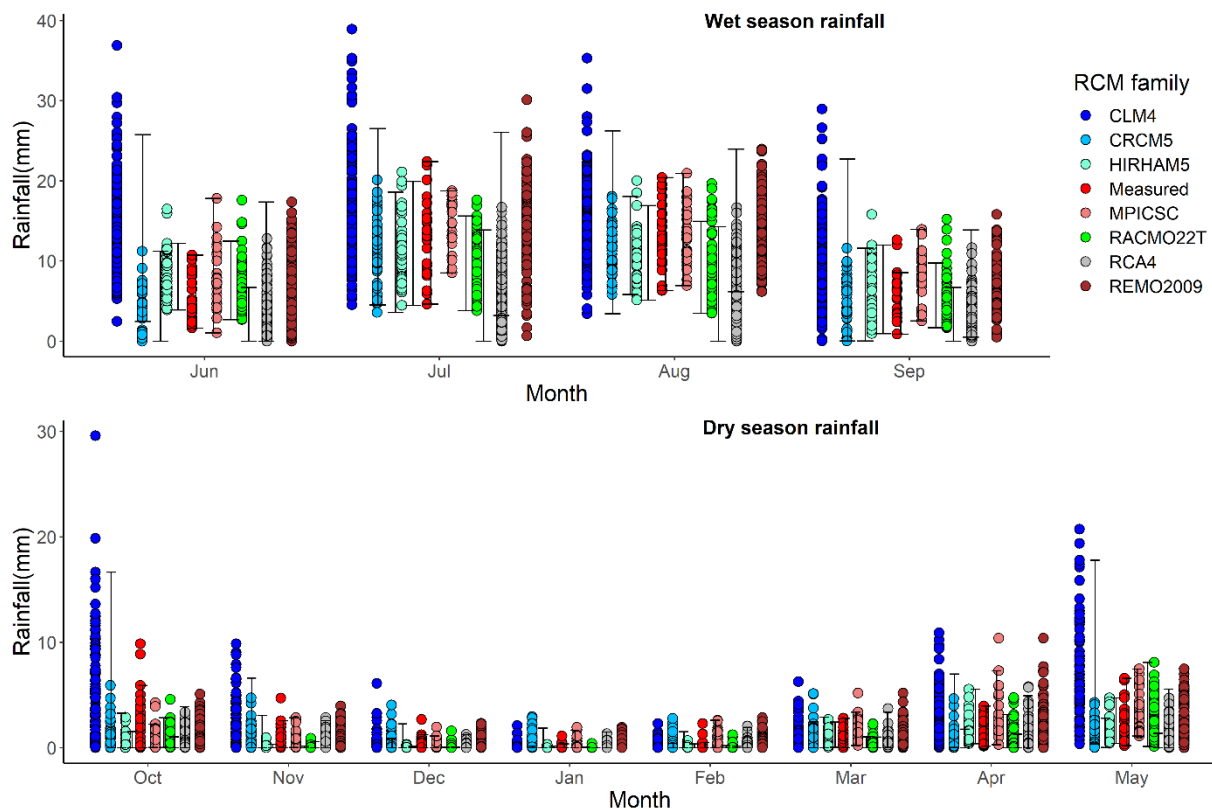


Figure 5-2: Comparisons of seasonal rainfall patterns of different RCMs with the observed rainfall at Debretabor station for the historical period (1980 to 2005).

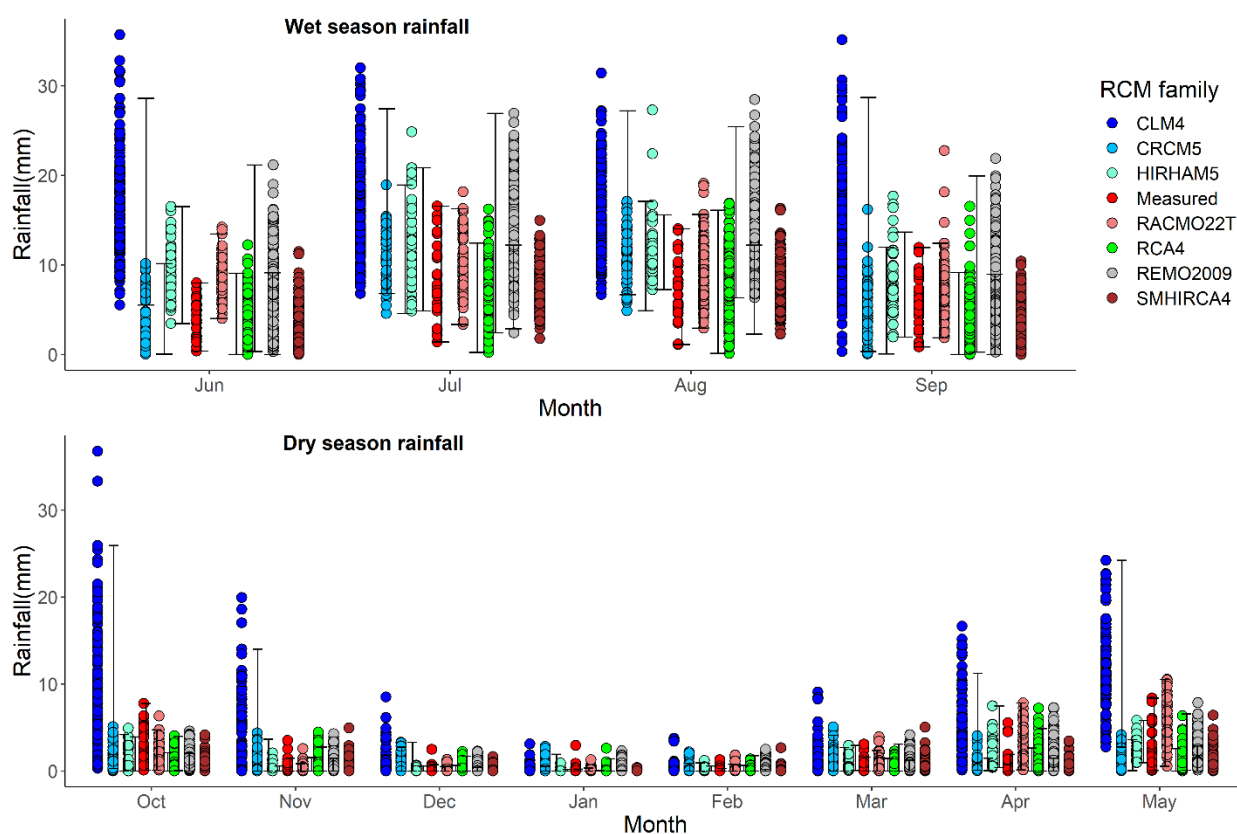


Figure 5-3: Comparisons of seasonal rainfall patterns of different RCMs with the observed rainfall at Adet station for the historical period (1980 to 2005).

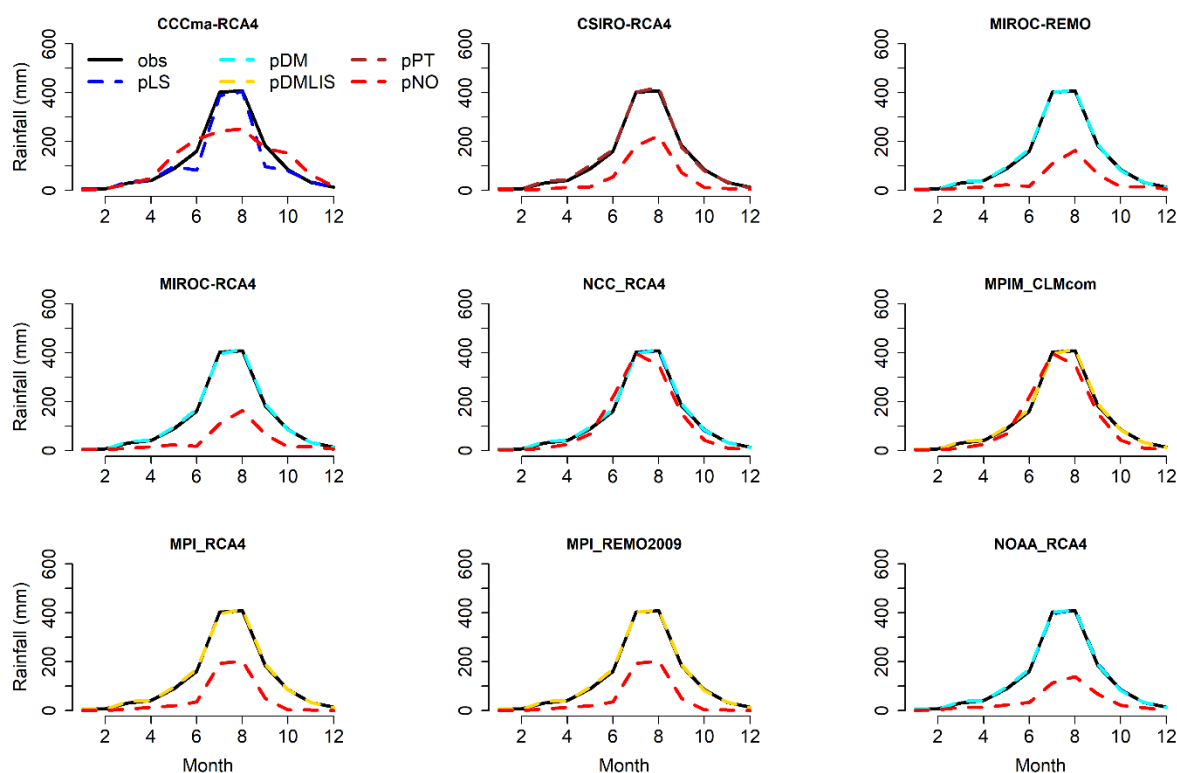


Figure 5-4: Exemplary plots presenting seasonal patterns and agreement of the bias-corrected mean monthly rainfall generated from regional climate model (1980 -2005) with the monthly rainfall.

mean of observed rainfall of Gumara catchment. The red line represent the monthly mean rainfall of different regional climate before bias correction is applied and the other colours represent after different bias correction methods are applied. Suitability of bias correction methods differ from one regional climate model to the other. Here, we presented the rainfall data generated from different regional climate that showed good agreement with observed rainfall at Debretabor station only as an example.

Table 5-1:List of selected GCMs, RCMs, applied bias correction (BC) methods, root mean square error values (RMSE) as computed using long-term (1980 -2005) monthly average observed and RCM generated rainfall data for Gilgelabay and Gumara catchments (1\* represent that the GCM-RCM data has only one RCP, either of RCP4.5 or RCP8.5).

Gilgelabay						
GCM/RCM	Institution Name	Expanded name of RCM	BC method	RMSE before BC	RSME value	Suitable GCM-RCM
CCCma/RCA4	Canadian climate model	Regional-scale model	pDM	3.28	0.17	2
			pLS		0.16	2
IPSL-M5/REMO2009	Institut Piere Simon Laplace	Regional Climate Model	pLS	1.69	0.16	1
IPSL/RCA4		Regional-scale model	pDM	1.69	0.16	2
MIROC/REMO2009	University of Tokyo, Japan	Regional Climate Model	pLS	5.31	0.22	1
	RCA4		pLS	5.31	0.24	2
NCC/RCA4	National climate center of China	Regional-scale model	pDM	5.38	0.24	2
NOAA/RCA4	Geophysical fluid dynamics laboratory of the US	Regional-scale model	pLS	4.75	0.23	2
			pLIS		0.23	2
<b>Total</b>						<b>16</b>
Gumara						
CCCma/RCA4	Canadian center for climate modeling and analysis	Regional-scale model	pLS	2.32	0.35	2
CSIRO/RCA4	Climate change information for Australia		pPT	3.23	0.23	2
MIROC/RCA4	RCA4	Regional Climate Model	pDM	6.4	0.16	2
MIROC/ REMO2009	University of Tokyo, Japan		pDM	4.9	0.13	1
MPIM/CCLM-4-8-17	Max Planck Institute for Meteorology	Climate limited area modeling community	pDMLIS	3.44	0.16	2

MPIM/REMO2009	Max Planck Institute for Meteorology	Regional Climate Model	pDMLIS	2.32	0.34	2
MPIM/RCA4	Max Planck Institute for Meteorology	Regional- scale model	pDMLIS	3.34	0.50	2
NCC/RCA4	National climate center of China		pLS	2.32	0.20	2
NOAA/RCA4	Geophysical fluid dynamics laboratory of the US		pLS	4.15	0.13	2
			pDM	4.15	0.23	2
<b>Total</b>						<b>19</b>

### 5.2.5. Climate change impact investigation

Thirty five bias corrected GCM-RCM outputs (19 for Gumara, 16 for Gilgelabay) were used as an input to the hydrologic model SWAT to investigate the future hydrologic balance of the two catchments. The major hydrologic components were analysed for the mid-term (2031-2060) and long-term (2065-2094) future. It is reported that projected results for future climate change differ among the different sets of GCM-RCM outputs resulting in considerable uncertainty (Huang 2014; Kisebe et al. 2019). This in turn results in variation of the projected water balance components depending on the GCM-RCM outputs used in the hydrologic model. For this reason, we calculated the annual ensemble mean of simulated water balance components for the mid-term (2031-2060) and long-term (2065-2094) to get a representative prediction. The SWAT model simulation results of the GCM-RCM-BC combination (19 for Gumara) and (16 for Gilgelabay) were averaged to get an ensemble mean for each of the catchments. Equation (1) below shows the applied procedure:

$$\phi_m = \int_{i=1}^n \left( \frac{(\phi_{rcm1} * f_{rcm1} + \phi_{rcm2} * f_{rcm2} + \dots + \phi_{rcmn} * f_{rcmn})}{f_{rcm1} + f_{rcm2} + \dots + f_{rcmn}} \right) \dots \dots \dots (1)$$

Where n stands for the number of regional climate models,  $\phi_m$  for the ensemble mean hydrologic variable (e.g. rainfall, GWQ, SURQ, ET, PET, PERC), and  $\phi_{rcm1}$ ,  $\phi_{rcm2}$ ,  $\phi_{rcmn}$

represent the value of hydrologic variable at the given regional climate model 1, 2, 3, ..., n and f represents the frequency of the regional climate model depending on the selected bias correction method.

The changes of the major water balance components were computed with reference to SWAT model simulated results using observed climate data (1985-2014) here after called baseline period. Tukey's multiple mean comparison test was applied to investigate the projected water balance changes. Here, factor variables named baseline, mid-term, and long-term were assigned for each year corresponding to the three time periods. Then a Tukey multiple mean comparison test (95% confidence level) that is based on a two way anova model (Yandell 1997) was applied between the baseline and mid-term, baseline and long-term, mid-term and long-term major water balance components and climate time series.

### **5.3. Results and discussions**

#### **5.3.1. Project changes of Rainfall and Temperature**

A combination of 7 GCM, 4 RCM, and 5 BC resulting in a total of 35 GCM-RCM-BC scenario outputs (19 for Gumara) and (16 for Gilgelabay) were used in SWAT to simulate the effect of climate change on the hydrologic balances of the two catchments considered. Rainfall comparison between measured and climate scenario data for the period 1980 to 2005 showed that there is no single bias correction method that performed best for all RCMs (Table 2). We observed variation in matching the measured mean monthly rainfall. In the case of CCCma-RCA4 and NCC-RCA4, all BC correction methods showed miss-matches (RMSE values vary between 1.53 to 3.34) on the mean monthly rainfall values except the pLS (Table 1) method. The pLS BC method showed relatively better matching of the mean value for each month than the other BC methods (RMSE < 0.35). Power transformation for rainfall (pPT) was the best BC method in fitting the mean rainfall values and maintaining the seasonal patterns in the case



of CSIRO-RCA4 outputs (Figure 4). The rainfall data from the family of MPIM-RCM (1980-2005) showed good agreement with the observed one in the case of pDMLIS and pDM BC methods, and pLS and pDM methods resulted in good performance in the case of NOAA-RCA4 outputs (Figure 4). Moreover, RCM outputs from CNRM, ICHEC, IPSL, and MOHC showed high variation in the seasonal patterns and mean monthly values of the rainfall compared to the observed ones ( $RMSE > 0.5$ ). The differences in the mean monthly rainfall values are very pronounced in June and September. There is also variation in the annual rainfall among different GCM-RCM outputs. As an example, the annual rainfall values significantly vary between MIROC and CSIRO families in case of Gumara (Figure 5). Annual rainfall outputs derived from MIROC family for the mid- and late-terms of the 21st are expected to increase significantly compared to the baseline average for both RCP4.5 and RCP8.5 ( $p\text{-value} < 0.001$ ). To the contrary, in the case of CSIRO family scenario, a significant decrease is expected (Figure 5).

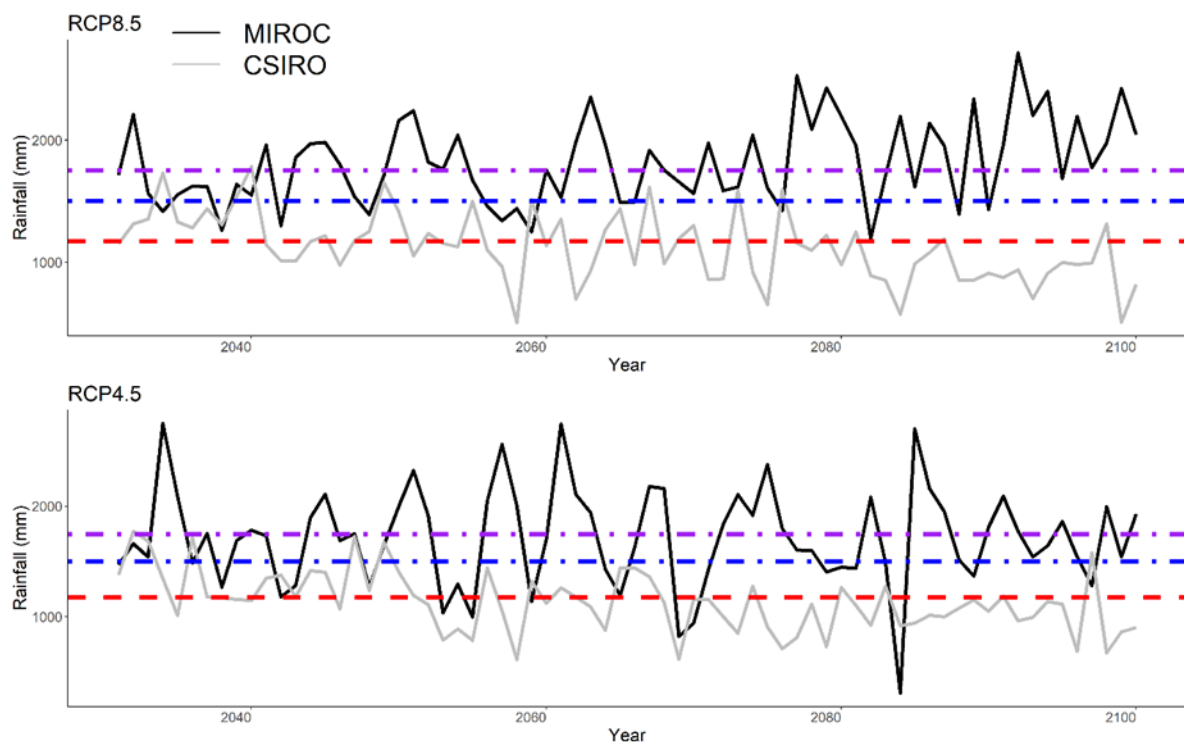


Figure 5-5: Sample plots showing how the projected annual rainfall varies between different GCMs (in this case MIROC and CSIRO outputs) in comparison with the 5% quantile (red

colour), 50% quantile (blue colour), and 95% quantile (purple colour) of the baseline annual rainfall. Baseline rainfall here refers to the measured rainfall during 1985 to 2014 in Debreabor station, which was the input rainfall data for the hydrological model.

There is also variation in the ensemble mean rainfall changes between the mid- and long-term of the century for both RCPs. Compared to the baseline average, the ensemble RCM mean rainfall of Gumara catchment under RCP4.5 is expected to increase by 4.4% and decrease by 0.7% during the mid-term and long-term of the 21st century, respectively. Similarly, an increase of 0.4% and a decrease of 2.2% for the mid-term and long-term periods, respectively, are expected under RCP8.5. The direction of rainfall changes are consistent with the findings of Roth et al. (2017) and Gebremeskel and Kebede (2018). Unlike the Gumara catchment, expected changes of the ensemble mean rainfall in Gilgelabay catchment under RCP8.5 are negative for both time periods. About 3% decline is expected for mid- and long-term of the century. Nevertheless, the overall average values for the two time periods will not change significantly compared to the baseline average. Similarly, Setegn et al. (2011) reported that there was no significance change on the ensemble median rainfall from 18 GCMs.

While, the direction of projected rainfall changes varies across the GCM-RCM outputs on all revealed a rising trend in both, minimum and maximum temperature. Setegn et al. (2011) also concluded that there is no consensus on the direction of rainfall changes of different GCMs. In this study, we noticed that each and every 30 years moving average maximum and minimum temperatures (for a data series from 1985 to 2100) is expected to be higher than the preceding one (Figure 7). The absolute temperature change varies between 1.3 to 2.7°C and 2.0 to 3.8°C for the mid- and long-term of the century, respectively. The model outputs showed a significant change from the baseline average during the long-term of the century. The mid-term projection will also deviate from the baseline average for all RCMs, but not as pronounced as for the long-term period. These findings are also confirmed for the entire Blue Nile basin (Roth et al. 2018). A similar study conducted on the Upper Blue Nile River basin by Kim and Kaluarachchi (2009)

reported an increase of 2.6°C for 2050s, which is close to our results. The slight differences on the temperature changes between the current study, Roth et al. (2017), and Kim and Kaluarachchi (2009) might be due to the differences in the future time window considered as well as the differences in GCMs outputs used for the studies. Our study is based on regional climate model results under the AR5 assumption report of (IPCC 2014), while Kim and Kaluarachchi (2009) used global climate model outputs under the (IPCC 2000) emission scenario.

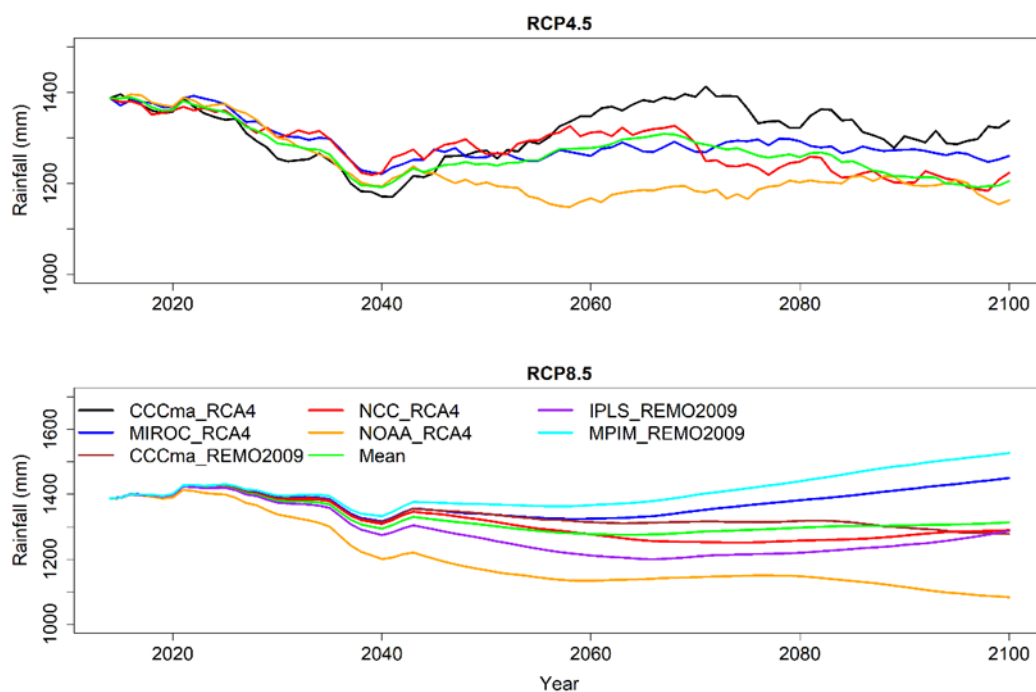


Figure 5-6: Thirty years moving average projected rainfall of different GCM-RCM outputs under the middle label (RCP 4.5) and the worst (RCP 8.5) concentration pathways (Gilgelabay).

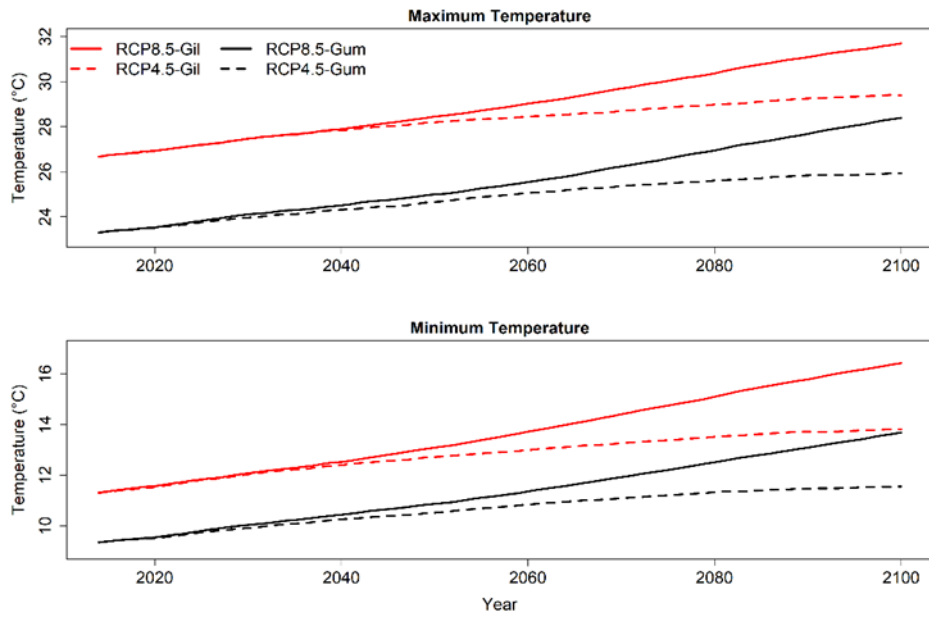


Figure 5-7: Thirty years moving average ensemble mean projected temperature of different GCM-RCM outputs under the middle level (RCP4.5, dashed lines) and high level (RCP8.5, solid lines) concentration pathways. Red colour represents Gilgelabay and black Gumara).

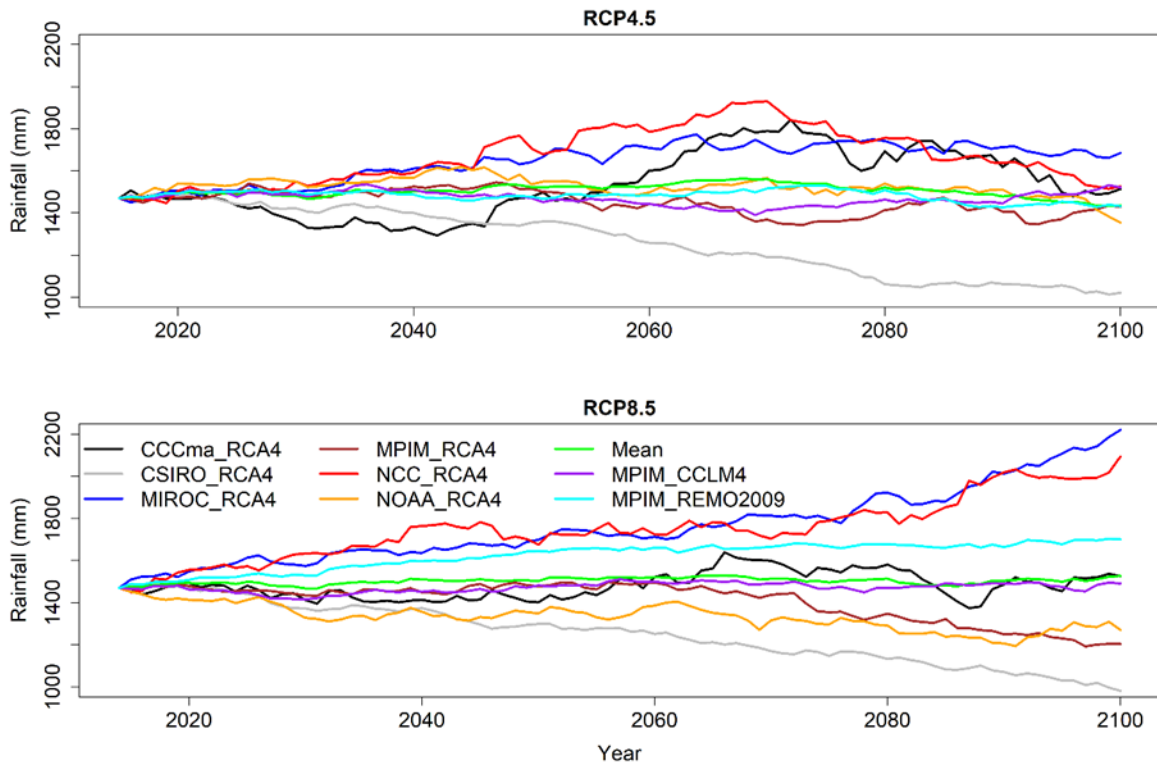


Figure 5-8: Thirty years moving average projected rainfall of different GCM-RCM outputs under the middle level (RCP4.5) and highest (RCP8.5) concentration pathway (Gumara).

### 5.3.2. Expected impacts of climate change on water balance components

To assess impacts on water balance components SWAT model simulation results for 19 and 16 bias-corrected GCM-RCMs for Gumara and Gilgelabay, respectively, were analysed, and ensemble means of the simulated results from all GCMs for middle level (RCP4.5) and highest level (RCP8.5) representative concentration pathways were illustrated.

Our results indicated various changes in the water balance components in the two catchments. The water yield is expected to rise for the mid-term of the century in the Gumara catchment under both RCP4.5 and RCP8.5. However, for the long-term period, a drop for RCP4.5 and a rise for RCP 8.5 are expected. These changes follow the direction of rainfall changes (Table 3). A small change in the rainfall amount could result in more pronounced changes of the water balance components. A 4.6% increase in the annual rainfall in Gumara catchment resulted about 6.8% increase in the water yield. Likewise, in Gilgelabay catchment, a 3% drop in rainfall for both mid-term and long-term was resulting in about 1% and 5% reduction in water yield, respectively under RCP8.5. There are clear differences in the projected rainfall and water balance changes between Gilgelabay and Gumara under the two representative concentration pathways. For example, in Gilgelabay catchment, the weighted ensemble mean rainfall values (for both mid- and long-term of the century) under RCP8.5 are expected to decrease by 3%, and these changes in turn affect the water yield to decrease by about 1 to 5% when compared to the baseline average. Whereas, in Gumara catchment, an increase for the mid-term and a decrease for the long-term are expected. These results suggest that the local conditions also contribute strongly to how the climate change signal affects water balance components.

Table 5-2: Average increase/ decrease in the SWAT simulated major water balance components and p-value (\*\*\*p-value  $\leq 0.001$ , \*\*p-value = 0.01, \*p-value = 0.05) computed based on Tukey multiple mean comparison method (95% confidence level) for the mid-term, long-term with reference to the baseline period, and between the mid-term and long-term of

the 21st century. The numbers represent the absolute change (first number) and p-value (second number), and the numbers in bold indicate significant changes.

Gumara						
	RCP 4.5		RCP 8.5		$\Delta$ between mid and long terms	
Variable	Mid-term-baseline	Long-term-baseline	Mid-term-baseline	Long-term-baseline	Mid-RCP4.5 – Long-RCP4.5	Mid-RCP8.5-Long-RCP8.5
Rainfall (mm)	66.10	-10.5	6.40	-32.90	76.53	38.46
Mean Temp °C	1.99***	2.72***	2.49***	4.70***	-0.72***	-2.21***
ET (mm)	-4.8	-11.80	-2.4	-15.43.9	7.02	12.98
GWQ (mm)	-70.3***	-97.75***	-61.8***	-93.48***	27.45	31.63
PERC(mm)	-83.62***	-118.04***	-73.28***	-111.42***	34.41	38.14
SURQ (mm)	161.52***	130.97***	89.0***	106.59***	30.55	-17.61.6
WYLD (mm)	67.35	-2.71	6.45	-20.88	69.97	27.33
Gilgelabay						
Rainfall (mm)	26.30	-35.34	-48.53	-42.82/0.87	38.3/0.7	-19.3/1.0
Mean Temp °C	2.07***	2.87***	2.72***	5.04***	-0.15	-2.33***
ET (mm)	-56.21***	-46.47***	-38.17***	-6.63	-9.75	-31.53/0.05
GWQ (mm)	14.39	-20.80	-15.31	-44.26	35.19	28.95
PERC(mm)	20.00	-31.00	-23.00	-65.27	52.25	42.28
SURQ (mm)	64,71***	48.43***	20.42	35.73***	16.27	-15.31
WYLD (mm)	84.83	14.07	-5.38	-35.36	70.76	29.97

**Impacts on groundwater:** During the baseline period, the groundwater accounts for more than 50% of the streamflow for each catchment (Tigabu et al. 2019). Under RCP4.5, the groundwater contribution to the streamflow (GWQ) is decreased. The decreases of GWQ vary between 3 and 57%. These decreases were observed even for positive changes in the projected rainfall. For instance, in the Gumara catchment, statistically significant decreases (high confidence, p-values = 0.001) for both time periods are likely (Table 3) while a slight increase in rainfall is expected. This implies that other inputs like temperature may affect the groundwater. However, the effect of temperature on groundwater is not easily measureable, but its effect can be inferred from other hydrologic components such as ET.

A positive or negative change of one hydrologic component could cause an effect on the other component. The correlation matrix computed for the major hydrologic components confirms this (Table 4). Considering the correlation of the hydrologic components with rainfall and temperature, GWQ shows very high positive correlation coefficient with rainfall and a slight negative correlation with temperature. Surprisingly, the ET correlation with temperature shows small positive (in Gilgelabay) and negative in case of Gumara. Temperature is therefore not the major driving factor for ET. While this is true for potential ET, actual ET also relies on the available water, which may be (seasonally) limited. Also an increase of rainfall intensity contributes to this, as it favors fast overland flow. The intended fast overland flow on the other hand is expected to reduce infiltration.

Table 5-3: Correlation matrix of hydrological processes computed using Pearson Correlation method for the time series (2031 -2100) for Gilgelabay and Gumara catchments (numbers in bold color shows either strong positive or negative correlation).

<b>Gilgelabay</b>						
	Rainfall	ET	SURQ	GWQ	WYLD	Mean temperature
Rainfall	1.00	<b>0.64</b>	<b>0.69</b>	<b>0.94</b>	<b>0.94</b>	-0.12
ET	<b>0.64</b>	1.00	0.10	0.44	0.38	0.01
SURQ	<b>0.69</b>	0.10	1.00	<b>0.64</b>	<b>0.80</b>	0.20
GWQ	<b>0.94</b>	0.44	<b>0.64</b>	1.00	<b>0.97</b>	-0.27
WYLD	<b>0.94</b>	0.38	<b>0.80</b>	<b>0.97</b>	1.00	-0.15
Mean temperature	-0.12	0.01	0.20	-0.27	-0.15	1.00

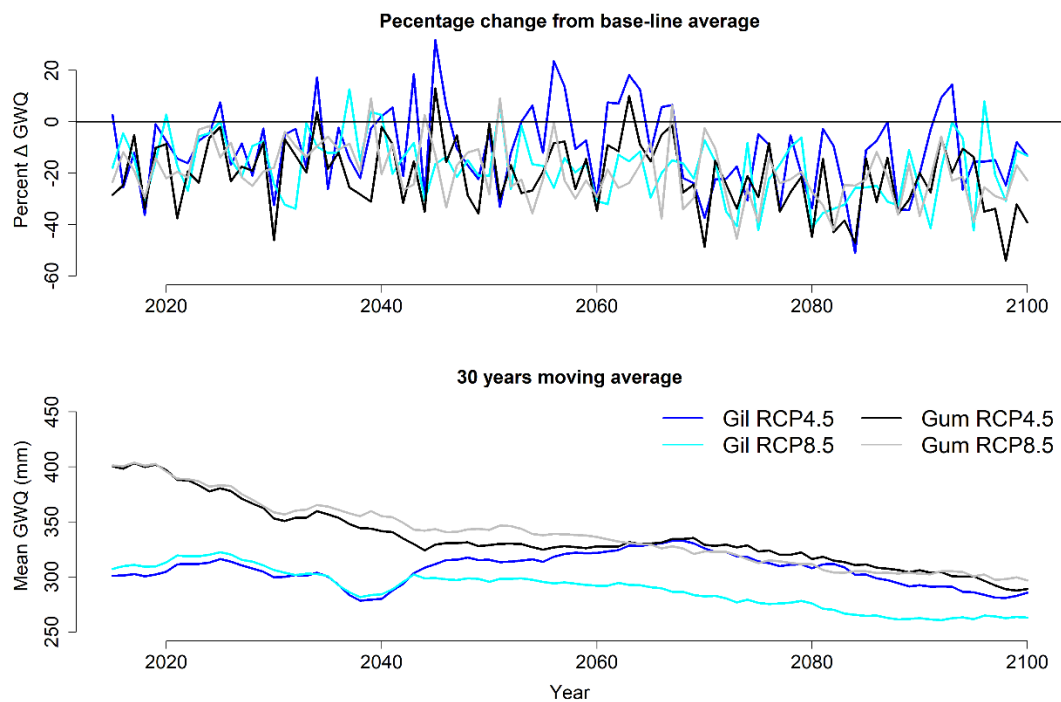
  

<b>Gumara</b>						
	Rainfall	ET	SURQ	GWQ	WYLD	Mean temperature
Rainfall	1.00	0.23	<b>0.80</b>	<b>0.75</b>	<b>0.98</b>	-0.17
ET	0.23	1.00	<b>0.06</b>	0.04	0.07	-0.15
SURQ	<b>0.80</b>	0.06	1.00	0.26	<b>0.81</b>	0.26
GWQ	<b>0.75</b>	0.04	0.26	1.00	<b>0.77</b>	<b>-0.53</b>
WYLD	<b>0.98</b>	0.07	<b>0.81</b>	<b>0.77</b>	1.00	-0.16
Mean temperature	-0.17	-0.15	0.26	<b>-0.53</b>	-0.16	1.00

Compared to the Gumara catchment, the changes in GWQ for Gilgelabay catchment are less pronounced. In fact, the likely changes are not significant for the two time periods under both RCPs. However the overall changes of rainfall show a high temporal variability from a decrease of -1 to -25% that in turn changes the GWQ from -3% to -57%. On the other hand, no significant increases are expected under RCP4.5 for both mid-term and long-term period (Table 3). The excepted decreases in GWQ in the mid-term for both RCPs can be explained with the increases of surface runoff for both catchments. Indeed, the increment or decrement of rainfall for the given time periods could be considered as the main driving force. The thirty years moving average values of GWQ show a decrease for both RCPs in both catchments and only a few years show higher GWQ than in the baseline for Gilgelabay catchment (Figure 9). The changes are more severe for the long-term period in case of Gilgelabay, and for both periods for Gumara (Figures 9, Table 3). From these results, one can notice that the increases/decreases in rainfall changes are propagating to the increases/decreases in GWQ, respectively for both RCPs. In summary, changes related to GWQ are dominantly negative for both catchments under the two RCPs, and these changes are being driven by the increasing level of rainfall intensity that could



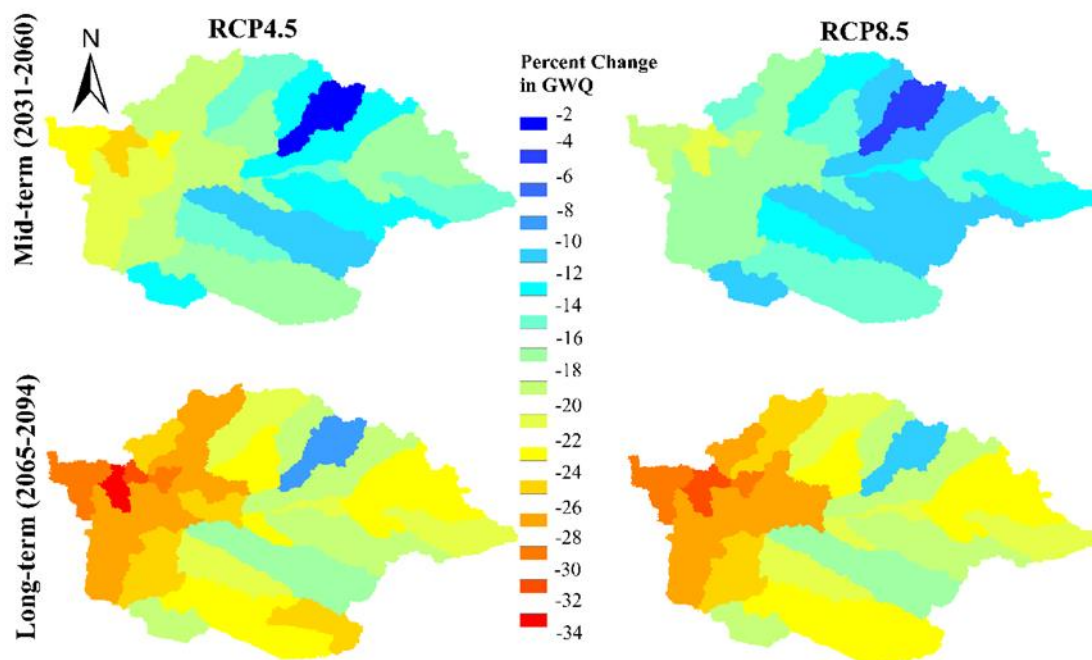
enhance SURQ. Moreover, the annual percolation will decrease under the given RCPs (Table 3) that would result in a drop of the water table of the shallow aquifer. Thus, a drop in the water table in turn would cause a reduction in the volume of groundwater discharge. The results are in agreement with findings of Setegn et al. (2011) and Koch and Cherie (2013) who applied climate change scenarios for the same region.



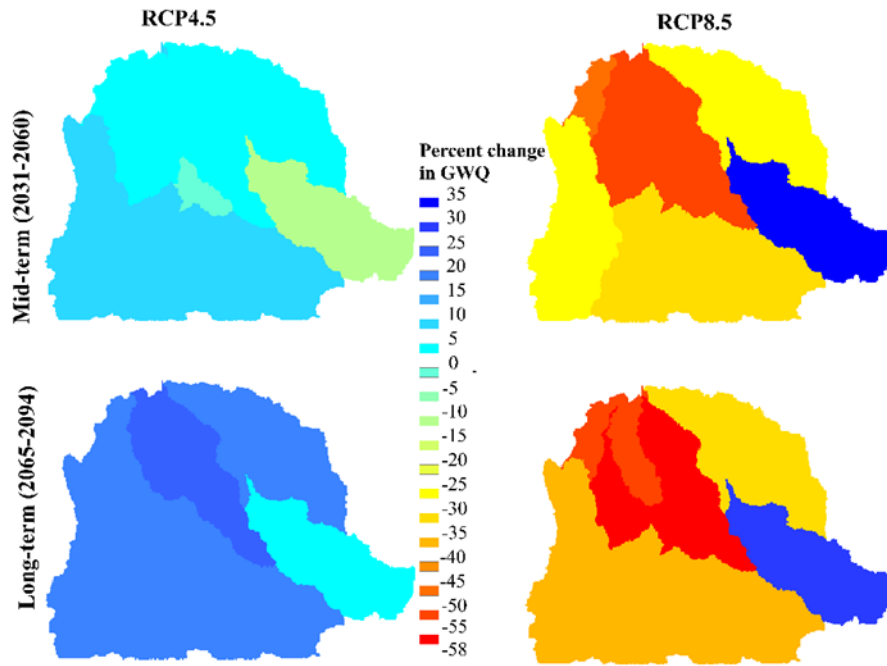
*Figure 5-9: The percentage changes of GWQ from baseline average and thirty years moving average for the ensemble mean of simulated GWQ under the middle label (RCP4.5) and worst (RCP8.5) for Gilgelabay (Gil) and Gumara (Gum).*

**Spatial patterns of changes in GWQ:** On top of the expected temporal changes in the GWQ in the study catchments, visible changes will also be expected in the spatial patterns. Influences of the projected rainfall and temperature vary from the highland to the lowland portion of the catchments. The projected changes are higher in the lowlands than in the highlands for both catchments. For Gumara catchment, the expected changes are negative and vary from -3% to -32% for both RCPs (Figure 10). Although, we expect differences in the magnitude of changes between RCP4.5 and RCP8.5 for both mid- and long-term periods, our result revealed that differences are small in the spatial pattern (Figure 10). To the contrary, in Gilgelabay

catchment, the degree of influences of the two RCPs on the spatial variability are differ considerably. Under RCP8.5, the intended changes will mostly be negative while positive changes are expected under RCP4.5 (Figure 11). Compared to Gumara, the percentage changes in Gilgelabay show a wider range that varies from 26% to -58%. This wide range of changes in Gilgelabay catchment can be explained by the variability in rainfall. Four rainfall stations were used for Gigelabay, while only one station was used for Gumara. However, Gumara shows a greater spatial diversification (Figure 10).



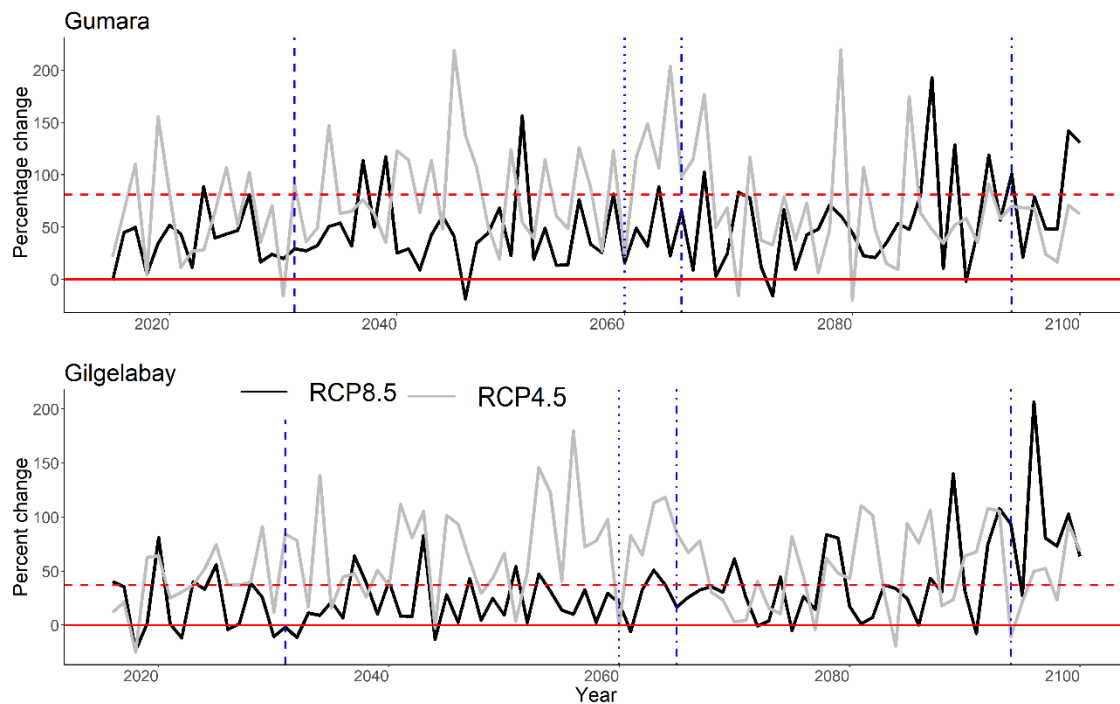
*Figure 5-10: Expected changes of GWQ on spatial patterns for the mid and long-terms of the century under RCP4.5 and RCP8.5 for Gumara catchment.*



*Figure 5-11: Expected changes of GWQ on spatial patterns for the mid and long-terms of the century under RCP4.5 and RCP8.5 for Gilgelabay catchment.*

**Surface runoff:** Under the assumption that agricultural management stays the same, our results indicated that the SURQ in Gumara catchment is more sensitive than the Gilgelabay (Figure 12). In the given two future time periods, significant increases are the likely in Gumara catchment. For instance, under RCP4.5, a 40% increase in catchment rainfall is expected to result in a 220% increase in SURQ and for the year 2045 (mid-term) time horizon. This change is associated with a 12% increase in the mean temperature. Likewise, under RCP8.5, a 27% increase in rainfall is likely to increase the SURQ by 156%, and the expected mean temperature change associated with this is about 2.3°C. For the case of Gilgelabay catchment, significant increasing changes are expected for the two time horizons under RCP4.5, and for the long-term under RCP8.5. To the contrary, no significant change is expected for mid-term under RCP8.5. Obviously, the SURQ response is more sensitive to the changes in rainfall than to changes in temperature (Table 3). Another study conducted by Conway (1996) about the impacts of climate variability on the Nile water resources reported that a 10% increase in rainfall in Blue

Nile basin was resulting an increase of 34% SURQ, and the relationship between change in rainfall and change in SURQ was nearly linear.



*Figure 5-12: Percentage changes of the simulated ensemble mean SURQ under RCP4.5 and RCP8.5 with reference to the baseline average simulation result for Gumara and Gilgelabay catchments (the dashed red line represents the standard deviation of the baseline surface runoff, while solid red line standardized mean =0). The vertical broken blue lines represents the beginning and ending years of the mid-term and long-term future periods.*

**Actual Evapotranspiration (ET):** Changes in projected temperature and rainfall can be translated to potential evapotranspiration (PET) and actual evapotranspiration. Results of the current study revealed that the overall annual PET is expected to rise significantly for all time periods and RCPs due to the significant increase of temperature. Actual ET was expected to increase with increasing temperatures. However, in this study we found a decrease in annual actual ET. Compared to the baseline average, all anticipated changes in actual ET are downward. The changes are significant for Gilgelabay catchment except for the long-term period under RCP8.5. To the contrary, the changes for Gumara catchment are not significant. This decline can be explained by a (seasonal) limitation of water availability that limits the

responses to warming (Cordon et al. 2020, Wagner et al., 2015). About 51% of ET takes place during the dry season (October to May), when less water is available. It is not uncommon to get less ET in areas where the available water volume is small, and the available water volume and soil moisture are regularly correlated with rainfall. For the current study, the decreases in the future ET changes in Gumara and Gilgelabay catchments are limited by the available water. A significant increase on SURQ, and a significant decrease in the soil moisture content are expected under both RCPs and time periods that will likely cause less ET. The projected ensemble mean rainfall datasets, show that the future rainy days are expected to decrease compared to the number of rainy days during the baseline period even though the expected changes of total annual rainfall is not significant. In Gumara catchment, the average number of days with none zero rainfall records was 170 during the baseline period, while 160 and 154 rainy days for the mid-term and long term, respectively. Likewise, in Gilgelabay catchment the future rainy days are expected to decrease with a slope of 0.03day which is about a drop by 7 to 10 days when compared to the baseline. This indicates that the rainfall intensity is expected to go up, which in turn causes high surface runoff and less ET. High intensity rainfall may reduce ET as there will be less water interception and soil moisture content. This can explain why less ET is simulated even for positive changes of rainfall. Furthermore, ET change rates differ among catchments depending on the land cover types and different underlying surfaces processes (Woldesenbet et al. 2017; Wagner et al. 2019). In response to the rises in the mean temperature, the future PET changes with reference to the baseline average are expected to increase. This was directly reflected by all PET changes in the two catchments.

#### **5.4. Conclusion**

In this study, we investigated the future (2031-2060, 2065- 2094) temporal and spatial changes of groundwater contribution to streamflow and of major water balance components in two catchments (Gilgelabay and Gumara) of the Lake Tana basin, in northwestern Ethiopia under

RCP4.5 and RCP8.5 using CORDEX datasets (CMPI5). Impacts on water resources were assessed using the hydrological model SWAT.

The groundwater contribution to streamflow is projected to decline while no or only slight changes on rainfall are expected. The study catchments are expected to experience decreases of groundwater contribution to streamflow and increases in surface runoff. Future number of rainy days are expected to decrease in both catchments under the two concentration pathways. However, actual ET demand is higher under rising temperature, the anticipated actual ET would decrease in both catchments due to water limitation.

Compared to the baseline average, the intended changes of groundwater contribution to streamflow for the mid-term and long-term time period are significant for Gumara, while these changes are not significant in Gilgelabay catchment under both RCPs. Anticipated changes of surface runoff will be significant for both catchments during the mid-term and long-term periods when compared to the baseline period. Comparing results between the mid-term results and the long-term periods, the differences are expected not to be significant. Only, the annual ET is expected to be significantly higher during long-term than the mid-term under RCP8.5.

Distinct spatial patterns are expected in the groundwater contribution to streamflow for the two catchments. The declines of groundwater contribution to streamflow will be higher in lowland portions of the two catchments than in the highlands.

As this impact assessment study considered multiple GCM-RCMs from the Coupled Model Intercomparison Project and assessed ensemble results, we believe that the results provide a range of projections that are relevant for future water management planning in the region.

All anticipated changes in the given hydrological components were modeled under the assumption that the current agricultural management practices and land cover conditions would not change. The projection showed that the anticipated future rainfall would be more intense

than during the baseline resulting in more surface runoff. Hence, to mitigate climate change impacts it can be recommended to apply agricultural management practices that enhance infiltration and lead to an increase of water storage.

## **6. General discussion and conclusion**

### **6.1. General discussion and conclusion**

Globally, fresh water resources are under growing pressure due to rising global water demands of the rapidly growing world population, improved living standards, changed consumption patterns, and expansion of irrigated agriculture (Mekonnen and Hoekstra 2016). On a global scale, over 2 billion people live in countries with high water stress representing (11% of the global average area) (WWAP 2019). Water availability of a country is usually reported as an annual average value and does not account for seasonal and spatial variability. Ethiopia is one of the countries with a significant seasonal variation of its water availability. The situation is critical in the Upper Blue Nile Basin due to inappropriate water management (Polanco et al. 2017; Woldesenbet et al. 2017). Even with an average annual rainfall in the basin of 1800 mm there is still a considerable water shortage during the dry season (Gebrehiwot et al. 2011).

**Were there significant long-term changes (1960-2015) in rainfall, streamflow, and lake outflow time series observable in the Lake Tana basin?**

One of the main purposes of this study was to investigate the temporal variability of the long-term rainfall, streamflow, and lake outflow records from 1960 to 2015.

Rainfall and discharge patterns

Rainfall time series differed between the stations. The seasonal Mann Kendal (MK) trend test results indicated that the direction of changes varies between the wet and dry season rainfall. During the rainy season, about 61% of the rainfall stations considered in this study showed an upward trend, but only 33% of the changes were significant. For the dry season, 17% of the stations had a significant decrease and only one station (Mekaneyesu) showed a significant



increase. The MK trends of the daily and annual data records were mainly upward but most were not significant. Overall, 44% were decreasing, 56% increasing, and 78% not significant.

Changes of streamflow (Abay/outflow, Gilgelaabay, Gumara, Megech, and Ribb) and lake level time series from 1960 to 2014 were analysed. Positive changes were observed for daily and annual streamflow time series of all catchments, however not all differences were significant. Only Megech and Gumara showed a significant increase of their annual and decadal mean values. The outflow from the lake decreased significantly during the 2010s.

Compared to previous studies the overall annual changes in the rainfall were found to be in agreement with results of Tesemma et al. (2010), Gebremichael et al. (2013), and Tekleab et al. (2013). All studies agreed that the overall changes of the rainfall in Upper Blue Nile were not significant from 1964 until 2005. We could also confirm the results of Tekleab et al. (2013) who reported a significant change for Gumara and no significant increase in streamflow in the Ribb catchment. For the lake outflow, the current study described a high variability of the decadal mean outflow from 1960 to 2014 and a non-significant upward change while the ten years moving average values during the 2010s showed a significant decrease.

Generally, the overall trends of streamflow were upward while no significant changes were observed for the basin rainfall. This implies that the driver for the changes of streamflow are land use/cover changes and changes of rainfall intensity. Agriculture has intensified and urbanization has increased. From 1973 to 2010, an expansion of the cultivated land and a decline of the woody shrub and forestlands was observed in the Lake Tana basin (Woldesembet et al. 2017). Similarly, Gashaw & Fentahun (2014) reported an increase on both cultivation land and land degradation in the Eastern Lake Tana basin. Another study carried out in the Gumara catchment by Wubie et al. (2016) addressed the land use/cover changes over two consecutive periods (1957–1985 and 1985–2005), they found considerable land use changes,

i.e. natural forests and wetland were converted to cultivated land and settlements. Gebremicael et al. (2013) confirmed that land use change has caused a significant increase of runoff and sediment load in the Upper Blue Nile during the last four decades. Those changes can enhance surface runoff by decreasing the infiltration rates. Moreover, the long-term rainfall records showed a decreasing trend of the number of rainy days in a year, while the total annual rainfall remains unchanged (Teshome et al. 2016). Changing rainfall properties like duration, intensity, and inter-event durations in the Blue Nile basin are also assumed to be an important reason for a change in streamflow in the region (Haile et al. 2010).

In summary, the hydrologic regime of the Lake Tana basin is changing overtime because of the significant changes on the land use pattern. However, rainfall changes were not significant.

### **How do the major water balance components vary on spatial and seasonal basis under different agricultural crops and land use/cover classes?**

The major economic activity in the Lake Tana basin is agriculture with different crops. We analyzed changes of the major water balance components between dry and wet seasons, and between the three catchments (Gilgelabay, Gumara, and Ribb) caused by different agricultural crops and other land use/cover classes and their spatial and seasonal variation

Changes in land use/cover alter surface roughness, albedo and other properties of a catchment, which in turn cause variability in the hydrological processes by changing the energy exchange between the atmosphere and land surface and net radiation (Luo et al. 2016). In the Lake Tana Basin, this study also shows changes in the hydrology due to different land use/covers.

**Groundwater recharge:** comparing the rate of groundwater recharge from agricultural crops and other land use/covers, we find that cereal crops like millet, teff, wheat, and barley show relatively higher recharge rates as compared to mixed crops, pulses, rice, grassland, and forest.

The changes on groundwater recharge are also reflected on the spatial patterns indicating variable effects of different land uses. Results show significantly higher GW recharge rate for agricultural areas than forest cover ones. These differences of the groundwater recharge rate among different LULC classes could be caused by the variability of the soil structure, water interception and transpiration demand of different vegetation covers. Agricultural activities can also increase infiltration due to tillage of the soil (Gumindoga et al. 2014).

**Surface runoff:** the surface runoff also shows considerable variability among the different land use classes and between the three catchments. Results show that hydrologic response units (HRUs) that include medium density urban settlements, farm settlements, and mixed cropland as the land use/cover class increased the magnitude of surface runoff. The differences in its magnitude vary significantly from one land use class to another one. Compared to other land use classes, the annual mean runoff magnitude on corn cover area is above all other land use classes. The differences vary from 14 mm to 83 mm and all are significant. Contrary to this, cereal crops such as teff, wheat, and barely show relatively low runoff. These differences can be explained by the lower runoff curve number value in the case of cereal and vice-versa in the case of corn. When we consider the effect runoff between the three catchments, our results show that Gumara catchment is the most vulnerable one followed by Ribb.

**Actual evapotranspiration (ET):** similar to groundwater recharge, ET also varies among different land use/cover classes. The annual mean values decrease from forest cover to agricultural land for all the three catchments. Among the agricultural crop, teff has the smallest amounts of average annual water loss by ET. The differences in ET values among the different crops and other land use classes could be a result of differences in water uptake, available water capacity, and leaf area indices.

Apart from changes of HRUs, the water balance components reflect the patterns of the rainfall distribution in the Gilgelabay catchment. The northern and south-western part of the catchment are characterized by high amount of groundwater recharge and surface runoff, as a result of the highest amount of rainfall in the catchment (Figure 3.5, 3.7, and 3.9). In the Gumara and Ribb catchments the spatial variation of the water balance components are not influenced by rainfall as only one rainfall station was used for the simulation, so that LULC and soil units have more influence on the spatial patterns of hydrologic components than rainfall. We found also significant seasonal variability of the hydrologic components. Because of the influence of the ITCZ position, about 80% of the rainfall falls during the summer (wet season), and this controls water availability in the catchments. More than 90% of the groundwater recharge and surface runoff and about 49% of the ET take place during the wet season. Therefore, the seasonal anomalies on the recharge and surface runoff processes in the region are largely correlated to the rainfall anomalies between the dry and wet seasons, while the overall ET variability between the two seasons is not pronounced. Base flow has substantial contribution to streamflow of the Lake Tana Basin.

In all the three catchments streamflow is dominated by base flow. Setegn et al. (2008) also found that the base flow contribution to streamflow is very high. However, there are differences between this study and Setegn et al. (2008). For example, Setegn et al. (2008) reported a 59% base flow contribution for Gilgelabay catchment, while 73% is found in the current study. Because of the differences of fitted model parameters between the three catchments, the base flow contribution to the streamflow varies.

In conclusion, this study proved that hydrologic processes (groundwater recharge, surface runoff, actual evapotranspiration) are significantly varying between cereal crops, leguminous plants, grassland, and forest covers. As an example, the degree of vulnerability to surface runoff is the highest in Gumara, and groundwater recharge is highest in Gilgelabay catchment. The

differences are weaker between the Gumara and Ribb catchments. Furthermore, the groundwater recharge, water yield, and surface runoff values varied between the dry and wet seasons in the three catchments.

**Do the groundwater and surface water systems interact with each other and how does the behavior of GW-SW interaction vary in space and time?**

By applying the SWAT model (Arnold et al. 1998; Arnold and Fohrer 2005) we found that groundwater has significant contribution to streamflow. However, we could not fully explain the bidirectional groundwater (GW)–surface water (SW) interaction. Moreover, the spatio-temporal flow dynamics of the groundwater were not addressed sufficiently. GW-SW interactions and the resulting exchange fluxes are often characterised by a high temporal and spatial variability (Krause et al. 2007). Therefore, we used a coupled GW-SW hydrologic model (SWAT-MODFLOW) (Bailey et al. 2016) to gain new insights into the spatio-temporal flow dynamics of groundwater-surface water interactions.

In this section we analyze the hydraulic connection between the aquifer and stream network, the spatio-temporal variation of GW-SW interactions and the differences of the GW-SW interaction between the three catchments.

The model efficiencies of the measured monthly streamflow are very good ( $NS > 0.7$ ) for all the three catchments (Table 4.1). Results showed that GW-SW interactions varied both on space and time. Groundwater recharge zones are mainly located in the highland areas. The potential head difference between the aquifer and the stream and other properties such as hydraulic conductivity, specific storage and initial groundwater head are the main controlling factors for the spatial variability of GW-SW interaction (Kim et al. 2008). The current study found most interactions between the GW and SW during the wet season. This high variability of the GW-SW interaction between the dry and wet months influences the water level in the

rivers. The dominant exchange is 170 (m<sup>3</sup>/day) from the aquifer to the stream system in the Gilgelaby catchment.

In Gumara and Ribb the exchange between aquifer and stream is bidirectional for all time steps. The Gumara catchment is largely controlled by the surrounding surface water system. In the downstream floodplain and reaches groundwater is discharged to the stream system (Figure 4.5). Dessie et al. (2014) reported that the floodplain of the Gumara catchment was recharged by the groundwater during the rainy season. Chebud and Melesse (2009) also reported that 0.09 billion cubic meter of water flow out of from floodplain aquifer to the Lake Tana during the wet season. The bidirectional flow of the Ribb catchment is more or less similar to the Gumara catchment. Since the early 1990s the temporal patterns showed significant changes for the entire year and during the dry season (magnitude and flow direction) for the two catchments (Figure 4.4, 4.5). Before the early 1990s the flow direction was from the stream to the aquifer and changed later. This decrease of flow from the river network to the aquifer and the change of direction from the aquifer to the stream system (annual and dry season) over time could be related to the increase of runoff. Recently the number of rainy days in a year are decreasing while the total rainfall amount did not change significantly, which in turn leads to more intensive rainfall and results in more surface runoff generation and less seepage to the aquifer system. Another notable result from this investigation is the strong dynamics of the exchange fluxes between the aquifer and the stream system on the daily time step (Figure 4.3). The high variability of the daily and seasonal GW-SW exchange rates might be attributed to a large variation in daily rainfall (coefficient of variation ranging from 100 to 200%) (refer to section 4.3.1).

Overall, we found a strong hydraulic connection between GW-SW systems and all the three catchments are characterized by a considerable spatio-temporal variability within and between the catchments. The annual temporal patterns and direction of the water fluxes in the

Gilgelabay catchment differs from the ones in the Gumara and Ribb catchments where negligible seepage from the stream was found.

### **How will future climate change affect the major water balance components of the Lake Tana basin?**

After the discussion of historical and current hydrologic conditions, in the following possible future changes of the major hydrologic components for two climate change scenarios are discussed for the mid-term (2031-2060) and long-term (2065-2094).

The mean annual temperature is expected to increase significantly while the ensemble annual mean rainfall from 19 (Gumara) and 16 (Gilgelabay) regional climate models shows only minor changes for the mid-term and long-term compared to the baseline period from 1985 to 2014.

**Impact on water balance:** With rising temperatures, one may expect more potential evapotranspiration (PET) and actual evapotranspiration (ET), which in turn could cause a drop of the groundwater contribution (GWQ) to the streamflow. Here, we analyse the model results for the major water balance components with the Mann Kendall trend test and the Tukey multiple mean comparison tests applied on the annual values of each hydrologic component.

The future annual mean temperature is expected to rise significantly ( $p\text{-value} < 0.05$ ) for both time windows and RCPs, which in turn will cause a significant increase of PET. To the contrary, our results show a decrease of the annual ET. Nevertheless, the projected declines are not statistically significant for Gumara, while the decrease is significant for the Gilgelabay catchment (Table 5.2). The GWQ is also anticipated to drop significantly ( $p\text{-value} < 0.05$ ) in Gumara, while no significant ( $p\text{-value} > 0.05$ ) decrease is expected in Gilgelabay except for the mid-term of RCP4.5. Significant increases will be expected for SURQ in both catchments. The expected changes of surface runoff are positive even under conditions of slightly lower rainfall. But the number of projected rainy days will decrease in both catchments. Future rainfall is

expected to be more intense than the rainfall during the baseline period. As a result, more surface runoff will be expected. Thus, the expected increase of runoff will have different implications on the other water balance components. Except for the mid-term of RCP4.5 in Gilgelabay, the groundwater contribution to the streamflow is expected to decrease for both catchments and both RCPs. The decrease in the Gumara catchment is significant, whereas it is not significant in Gilgelabay. ET was expected to increase with increasing temperatures. However, we found a decrease of ET in both catchments. This decline was observed even for positive changes of the projected rainfall because water availability limited the responses to warming (Condon et al. 2020, Wagner et al., 2015). About 51% of ET takes place during the dry season (October to May), when less water is available. These decreases of ET and GWQ highlight that the larger increase on SURQ limits the availability of water for other hydrologic processes. Expected changes of water yield will not be significant as the increase of surface runoff will be compensated by the decrease of GWQ and for both catchments. Moreover, we found a decrease of annual percolation and soil moisture that could result in a drop of the water table of the shallow aquifer. Thus, a decrease of the water table and soil moisture in turn would cause a reduction of the groundwater discharge and evapotranspiration. Setegn et al. (2011) also reported a decrease on the future GWQ under A1B and B scenarios outputs from GFDL and MPI.

In general, the small changes on rainfall in the scenario data will result in a significant change of the major hydrologic components. The temperature effect seems smaller than the rainfall effect. However, potential evapotranspiration (PET) is significantly higher under the two RCPs.

**Spatial patterns of changes in GWQ:** The impact of climate change is variable in space. Effects of rainfall and temperature changes on GWQ vary from the highlands to the lowlands



in the two catchments with more pronounced effects in the lowlands than in the highlands (Figure 5.10, 5.11). For the Gumara catchment we expect a decrease for the two future time periods and a slight increase for the mid-term period under RCP4.5 in Gilgelabay catchment. The differences between the two catchments could be related to the different local climates, static factors such as topography and slope.

Overall, the significant increase of the projected temperature and the small changes of the rainfall amount and intensity are expected to change the major water balance components. Surface runoff and groundwater contribution to the streamflow are expected to change in opposite directions. Here, increased surface runoff primarily contributes to a reduction of groundwater contribution to the streamflow.

## **6.2. General Conclusion**

This PhD thesis provides an additional understanding and new information about the past, present, and future hydrologic perspectives of the Lake Tana Basin. The topics covered includes statistical analyses of hydrometeorological time series, impacts of agricultural crops on hydrology, groundwater and surface water interaction, and impact of climate change on water resource in the Lake Tana Basin. The physically based hydrologic models SWAT and SWAT-MODFLOW were set up to model the past, the present and future hydrologic components in the Lake Tana basin. The models were calibrated and validated with measured streamflow data from the three catchments with satisfactory results. The key findings are:

Long-term hydrometeorological data analyses provide insight into the spatial and temporal patterns of the climate and hydrologic variables of the past and the results can be useful for managing possible the future impacts. From the statistical point of view, the hydrologic behaviour of the study area is highly variable in space and time. The rainfall and streamflow changes over time vary among annual, dry and wet seasons as well as daily rainfall and

streamflow. Historical rainfall records from 1960-2015 showed annual rainfall changes were not statistically significant for the whole catchment, but many single rainfall stations showed significant changes of the seasonal values. Unlike the annual rainfall records, streamflow time series revealed considerable changes on decadal time steps.

The models SWAT and SWAT-MODFLOW help to understand the spatial and seasonal patterns of the hydrologic components under different land cover/use and climate change conditions. Modelled results revealed a substantial contribution of groundwater to the hydrologic systems in the three catchments. Moreover, the different agricultural crops had different influence on spatial and seasonal patterns of hydrological variables. Some of them like cereal crops enhanced groundwater recharge, while others such as leguminous plants favoured surface runoff. Therefore, the future water availability could also be affected by the types of cultivated crops.

The coupled hydrologic models indicated that the surface water and groundwater systems interacted with each other with a high spatio-temporal variability. The anomalies were significantly higher on daily time step than monthly or yearly. However, this coupled model was not used for climate change impact study due to its high computational run time demand of the model to get the desired output. We used an ensemble average of 35 rainfall and temperature outputs from 35 regional climate model to minimize uncertainties associated with individual RCM (Kling et al. 2012). Due to this, use of the coupled hydrologic model was not feasible under the given time frame.

Understanding the availability of water resources under global climate change conditions can provide new insights for policy makers and water managers. This study therefore simulates different climate scenarios for the study region. Our intention was to understand how the major water balances components respond to future rainfall and temperature changes. The mean

temperature is expected to rise higher than the global average, while the rainfall is not expected to change significantly. We found that, the groundwater contribution to the streamflow and actual evapotranspiration tend to decrease whereas the surface runoff is likely to increase. Hence, appropriately accounting for the major water balance components in the context of climate change is of great importance when considering the future management and planning of water resources. Secondly, it is highly advisable to take appropriate measures to mitigate climate change impacts, e.g. implement water conservation measures, to store the expected increase of surface runoff and minimize soil erosion.

Overall, the hydrologic modeling methods and results that were based on specific agricultural crop cover and different climate options have diverse applicability for similar areas worldwide that are dominantly influenced by agricultural crops to design proper future water management plans. Moreover, results from the coupled hydrologic model also enhance our level of understanding on the flow dynamics of groundwater and surface water interaction on different temporal scales in the current study area and it helps to explain the interconnected hydrologic processes on other catchments in Ethiopia and Africa. Thus, the methodological approaches followed in this study could be transferred to such other regions.

Use of hydrological research outputs for decision making processes requires understanding the level of uncertainty associated with applied research methodology, quality and available input data, and hydrologic model parameters. Uncertainties associated with hydrologic modeling results in data scarce regions like that of the current study area are expected to be high level. Maximum effort was put to minimize uncertainties associated with the hydrologic model parameters through model calibration and validation using the available limited data. Nevertheless, we believe that further improvement could be possible by enhancing the database

system through regular measurement of groundwater table elevation, withdrawal and stream stage values.

In general, this study proved that the hydrology of the region was changed overtime due to escalations of agriculture, which in turn was derived by the rapid population growth. These changes are expected to be amplified in the future due to climate change unless appropriate agricultural practice and water resources management are designed to cope up with the anticipated changes. In this research, crop types were identified according to their impact on groundwater recharge, surface runoff generation, and evaporative demands, which would be a good insight to design proper future agricultural and water management practices in the study region and other similar areas that are under the pressure of intensive agriculture. The hydrologic models were developed considering agricultural crop variability considering their topographic variations and growing suitability of individual crops and finally came up with significance variances of influences on the hydrologic cycle. Thus, it is suggested to transfer this methodological approach to similar regions that are under rapid population growing pressure and agricultural intensification.

### **6.3. A look forward**

More than three million inhabitants of the Lake Tana basin put a high pressure on the water resource in the basin. This research tried to address hydrologic changes of the past, present and anticipated future in the basin. One key aspect considered was anticipated hydrological changes under global warming. Our results revealed that groundwater discharge is expected to decrease whereas surface runoff is expected to increase. However, still groundwater is the only reliable source of water for domestic, agricultural and industrial uses in the larger part of basin, especially in the rural area. Consequently, value of groundwater is expected to increase in the coming future as population is rapidly growing in the region. Therefore, future water

management and planning should consider combined use of surface water and groundwater. To come up with reliable management plans, scientific research outputs are required. Among others, detail investigation of groundwater-surface water flow dynamics by considering, rate of water withdrawal, temporal variability of groundwater table, soil moisture, surface water, and associated extreme condition is still required. Thus, the future research direction could be coupled model application and extreme flow analysis based on regularly measured data.

## References

- Abate, M., Nyssen, J., Steenhuis, T.S., Moges, M.M., Tilahun, S.A., Enku, T. and Adgo, E., 2015. Morphological changes of Gumara River channel over 50 years, upper Blue Nile basin, Ethiopia. *Journal of Hydrology*, 525, pp.152-164.
- Abbaspour, K.C., Vejdani, M., Haghighat, S. and Yang, J., 2007, December. SWAT-CUP calibration and uncertainty programs for SWAT. In MODSIM 2007 international congress on modelling and simulation, modelling and simulation society of Australia and New Zealand (pp. 1596-1602).
- Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S.R.I.N.I.V.A.S.A.N.B., Srinivasan, R., Yang, H. and Kløve, B., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology*, 524, pp.733-752.
- Abdo, K.S., Fiseha, B.M., Rientjes, T.H.M., Gieske, A.S.M. and Haile, A.T., 2009. Assessment of climate change impacts on the hydrology of Gilgel Abay catchment in Lake Tana basin, Ethiopia. *Hydrological Processes: An International Journal*, 23(26), pp.3661-3669.
- Abera, W., Tamene, L., Abegaz, A. and Solomon, D., 2019. Understanding climate and land surface changes impact on water resources using Budyko framework and remote sensing data in Ethiopia. *Journal of Arid Environments*, 167, pp.56-64.
- Adem, A.A., Tilahun, S.A., Ayana, E.K., Worqlul, A.W., Assefa, T.T., Dessu, S.B. and Melesse, A.M., 2016. Climate change impact on sediment yield in the Upper Gilgel Abay catchment, Blue Nile Basin, Ethiopia. In *Landscape dynamics, soils and hydrological processes in varied climates* (pp. 615-644). Springer, Cham.
- ADSWE (Amhara Design and Surevision Works Enterprise), 2017. Spatial data of land use and soil at the scale of 1: 50,000. Bahir Dar.
- Ahring, T.S. and Steward, D.R., 2012. Groundwater surface water interactions and the role of phreatophytes in identifying recharge zones. *Hydrology and Earth System Sciences*, 16(11), pp.4133-4142.
- Alemayehu, T., McCartney, M. and Kebede, S., 2009. Simulation of water resource development and environmental flows in the Lake Tana Subbasin. *Improved Water and Land Management in the Ethiopian Highlands: Its Impact on Downstream Stakeholders Dependent on the Blue Nile*, p.23.

- Alemayehu, T., McCartney, M. and Kebede, S., 2010. The water resource implications of planned development in the Lake Tana catchment, Ethiopia. *Ecohydrology & Hydrobiology*, 10(2), pp.211-221.
- Ali, R., McFarlane, D., Varma, S., Dawes, W., Emelyanova, I., Hodgson, G. and Charles, S., 2012. Potential climate change impacts on groundwater resources of south-western Australia. *Journal of Hydrology*, 475, pp.456-472.
- AWWCE (Amhara Water Works Construction Enterprise) , 2016. Well drilling well-log, well development, pumping test and completion reports of existing water scheme in the Lake Tana basin. Bahir Dar, Ethiopia.
- Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development 1. *JAWRA Journal of the American Water Resources Association*, 34(1), pp.73-89.
- Arnold, J.G. and Fohrer, N., 2005. SWAT2000: current capabilities and research opportunities in applied watershed modelling. *Hydrological Processes: An International Journal*, 19(3), pp.563-572.
- Arora, M., Kumar, R., Malhotra, J. and Kumar, N., 2014. Correlations of Stream Flow and Climatic Variables for a Large Glacierized Himalayan Basin. *Journal of Water Resource and Protection*, 6(14), p.1326.
- Asfaw, A., Simane, B., Hassen, A. and Bantider, A., 2017. Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin. *Weather and Climate Extremes*.
- Arsiso, B.K., Tsidu, G.M., Stoffberg, G.H. and Tadesse, T., 2017. Climate change and population growth impacts on surface water supply and demand of Addis Ababa, Ethiopia. *Climate Risk Management*, 18, pp.21-33.
- Bachmair, S. and Weiler, M., 2012. Hillslope characteristics as controls of subsurface flow variability. *Hydrology and Earth System Sciences*, 16(10), p.3699.
- Bailey, R.T., Wible, T.C., Arabi, M., Records, R.M. and Ditty, J., 2016. Assessing regional-scale spatio-temporal patterns of groundwater–surface water interactions using a coupled SWAT-MODFLOW model. *Hydrological Processes*, 30(23), pp.4420-4433.
- Bailey, R., Rathjens, H., Bieger, K., Chaubey, I. and Arnold, J., 2017. SWATMOD-Prep: Graphical user interface for preparing coupled SWAT-MODFLOW simulations. *JAWRA Journal of the American Water Resources Association*, 53(2), pp.400-410.
- Bates, D.M., 2010. *lme4: Mixed-effects modeling with R*. Springer Page:, Madison, WI, USA

- Berg, P., Feldmann, H. and Panitz, H.J., 2012. Bias correction of high resolution regional climate model data. *Journal of Hydrology*, 448, pp.80-92.
- Berhanu, B., Seleshi, Y. and Melesse, A.M., 2014. Surface water and groundwater resources of Ethiopia: potentials and challenges of water resources development. In *Nile River Basin* (pp. 97-117). Springer, Cham.
- Berihun, M.L., Tsunekawa, A., Haregeweyn, N., Meshesha, D.T., Adgo, E., Tsubo, M., Masunaga, T., Fenta, A.A., Sultan, D., Yibeltal, M. and Ebabu, K., 2019. Hydrological responses to land use/land cover change and climate variability in contrasting agro-ecological environments of the Upper Blue Nile basin, Ethiopia. *Science of The Total Environment*, 689, pp.347-365.
- Beyene, T., Lettenmaier, D.P. and Kabat, P., 2010. Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios. *Climatic change*, 100(3-4), pp.433-461.
- Birsan, M.V., Molnar, P., Burlando, P. and Pfaundler, M., 2005. Streamflow trends in Switzerland. *Journal of hydrology*, 314(1-4), pp.312-329.
- Björklund, G., 2001. Water management in developing countries-policy and priorities for EU development cooperation. *SIWI report*, 12.
- Bovolo, C.I., Parkin, G. and Sophocleous, M., 2009. Groundwater resources, climate and vulnerability. *Environmental Research Letters*, 4(3), p.035001.
- Brookes, J.D. and Carey, C.C., 2015. Ensure availability and sustainable management of water and sanitation for all. *UN Chronicle*, 51(4), pp.15-16.
- Change, I.C., 2014. Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, USA.
- Chatfield, C., 2004. *The analysis of time series: an introduction Sixth Edit.*, Boca Raton London New York, Washington DC: Chapman and Hall/CRC.
- Chebud, Y.A. and Melesse, A.M., 2009. Numerical modeling of the groundwater flow system of the Gumera sub-basin in Lake Tana basin, Ethiopia. *Hydrological Processes: An International Journal*, 23(26), pp.3694-3704.
- Chenhua, S., 2015. Analysis of detrended time-lagged cross-correlation between two nonstationary time series. *Physics Letters A*, 379(7), pp.680-687.
- Chunn, D., Faramarzi, M., Smerdon, B. and Alessi, D.S., 2019. Application of an Integrated SWAT–MODFLOW Model to Evaluate Potential Impacts of Climate Change and



- Water Withdrawals on Groundwater–Surface Water Interactions in West-Central Alberta. *Water*, 11(1), p.110.
- Comino, J.R., Iserloh, T., Lassu, T., Cerdà, A., Keestra, S.D., Prosdocimi, M., Brings, C., Marzen, M., Ramos, M.C., Senciales, J.M. and Sinoga, J.R., 2016. Quantitative comparison of initial soil erosion processes and runoff generation in Spanish and German vineyards. *Science of the Total Environment*, 565, pp.1165-1174.
- Condon, L.E., Atchley, A.L. & Maxwell, R.M., 2020. Evapotranspiration depletes groundwater under warming over the contiguous United States. *Nat Commun* 11, 873. <https://doi.org/10.1038/s41467-020-14688-0>
- Conway, D. and Hulme, M., 1993. Recent fluctuations in rainfall and runoff over the Nile sub-basins and their impact on main Nile discharge. *Climatic change*, 25(2), pp.127-151.
- Conway, D., 1996. The impacts of climate variability and future climate change in the Nile Basin on water resources in Egypt. *International Journal of Water Resources Development*, 12(3), pp.277-296.
- Costa, K., Russell, J., Konecky, B., & Lamb, H., 2014. Isotopic reconstruction of the African Humid Period and Congo Air Boundary migration at Lake Tana, Ethiopia. *Quaternary Science Reviews*, 83, pp.58–67.
- Cuthbert, M.O., Gleeson, T., Moosdorf, N., Befus, K.M., Schneider, A., Hartmann, J. and Lehner, B., 2019a. Global patterns and dynamics of climate–groundwater interactions. *Nature Climate Change*, 9(2), p.137.
- Cuthbert, M.O., Taylor, R.G., Favreau, G., Todd, M.C., Shamsudduha, M., Villholth, K.G., MacDonald, A.M., Scanlon, B.R., Kotchoni, D.O.V., Vouillamoz, J.M. and Lawson, F.M.A., 2019b. Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. *Nature*, 572(7768), p.230.
- Dargahi, B. and Setegn, S.G., 2011. Combined 3D hydrodynamic and watershed modelling of Lake Tana, Ethiopia. *Journal of hydrology*, 398(1), pp.44-64.
- Chunn, D., Faramarzi, M., Smerdon, B. and Alessi, D.S., 2019. Application of an integrated SWAT–MODFLOW model to evaluate potential impacts of climate change and water withdrawals on groundwater–Surface water interactions in West-Central Alberta. *Water*, 11(1), p.110.
- De Graaf, I.E.M., Van Beek, L.P.H., Wada, Y. and Bierkens, M.F.P., 2014. Dynamic attribution of global water demand to surface water and groundwater resources:

- Effects of abstractions and return flows on river discharges. *Advances in water resources*, 64, pp.21-33.
- Dersseh, M.G., Kibret, A.A., Tilahun, S.A., Worqlul, A.W., Moges, M.A., Dagnaw, D.C., Abebe, W.B. and Melesse, A.M., 2019. Potential of Water Hyacinth Infestation on Lake Tana, Ethiopia: A Prediction Using a GIS-Based Multi-Criteria Technique. *Water*, 11(9), p.1921.
- Dessie, M., Verhoest, N.E., Pauwels, V.R., Adgo, E., Deckers, J., Poesen, J. and Nyssen, J., 2015. Water balance of a lake with floodplain buffering: Lake Tana, Blue Nile Basin, Ethiopia. *Journal of Hydrology*, 522, pp.174-186.
- Déqué, M., Rowell, D.P., Lüthi, D., Giorgi, F., Christensen, J.H., Rockel, B., Jacob, D., Kjellström, E., De Castro, M. and van den Hurk, B.J.J.M., 2007. An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections. *Climatic Change*, 81(1), pp.53-70.
- Dile, Y.T., Berndtsson, R. and Setegn, S.G., 2013. Hydrological response to climate change for Gilgelabay river, in the Lake Tana basin-upper blue Nile basin of Ethiopia. *PloS one*, 8(10).
- Dile, Y.T., Rockström, J. and Karlberg, L., 2016. Suitability of water harvesting in the Upper Blue Nile Basin, Ethiopia: A first step towards a mesoscale hydrological modeling framework. *Advances in Meteorology*, 2016.
- Dile, Y.T., Tekleab, S., Ayana, E.K., Gebrehiwot, S.G., Worqlul, A.W., Bayabil, H.K., Yimam, Y.T., Tilahun, S.A., Daggupati, P., Karlberg, L. and Srinivasan, R., 2018. Advances in water resources research in the Upper Blue Nile basin and the way forward: A review. *Journal of hydrology*, 560, pp.407-423.
- Döll, P., 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environmental Research Letters*, 4(3), p.035006.
- Duvert, C., Jourde, H., Raiber, M. and Cox, M.E., 2015. Correlation and spectral analyses to assess the response of a shallow aquifer to low and high frequency rainfall fluctuations. *Journal of Hydrology*, 527, pp.894-907.
- Ebrahim, G.Y., Jonoski, A., van Griensven, A. and Di Baldassarre, G., 2013. Downscaling technique uncertainty in assessing hydrological impact of climate change in the Upper Beles River Basin, Ethiopia. *Hydrology Research*, 44(2), pp.377-398.
- Eckhardt, K. and Arnold, J.G., 2001. Automatic calibration of a distributed catchment model. *Journal of hydrology*, 251(1-2), pp.103-109.

- Ehtiat, M., Mousavi, S.J. and Srinivasan, R., 2018. Groundwater modeling under variable operating conditions using SWAT, MODFLOW and MT3DMS: A catchment scale approach to water resources management. *Water resources management*, 32(5), pp.1631-1649.
- Elshamy, M., Seierstad, I.A. and Sorteberg, A., 2009. Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. *Hydrol. Earth Syst. Sci.*, 13, pp.551–565, 2009.
- Ely, D.M. and Kahle, S.C., 2012. Simulation of groundwater and surface-water resources and evaluation of water-management alternatives for the Chamokane Creek basin, Stevens County, Washington. US Geological Survey Scientific Investigations Report, 5224, p.74.
- Fan, Y., Toran, L. and Schlische, R.W., 2007. Groundwater flow and groundwater-stream interaction in fractured and dipping sedimentary rocks: Insights from numerical models. *Water resources research*, 43(1).
- Field, C.B., V.R. Barros, K.J. Mach, M.D. Mastrandrea, M. van Aalst, W.N. Adger, D.J. Arent, J. Barnett, R. Betts, T.E. Bilir, J. Birkmann, J. Carmin, D.D. Chadee, A.J. Challinor, M. Chatterjee, W. Cramer, D.J. Davidson, Y .O. Estrada, J.-P . Gattuso, Y . Hijioka, O. Hoegh-Guldberg, H.Q. Huang, G.E. Insarov, R.N. Jones, R.S. Kovats, P . Romero-Lankao, J.N. Larsen, I.J. Losada, J.A. Marengo, R.F . McLean, L.O. Mearns, R. Mechler, J.F . Morton, I. Niang, T . Oki, J.M. Olwoch, M. Opondo, E.S. Poloczanska, H.-O. Pörtner, M.H. Redster, A. Reisinger, A. Revi, D.N. Schmidt, M.R. Shaw, W. Solecki, D.A. Stone, J.M.R. Stone, K.M. Strzepek, A.G. Suarez, P . Tschakert, R. Valentini, S. Vicuña, A. Villamizar, K.E. Vincent, R. Warren, L.L. White, T.J. Wilbanks, P .P . Wong, and G.W. Yohe, 2014. Technical summary. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*[Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y .O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P .R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY , USA, pp. 35-94.
- Gashaw, T. and Fentahun, T., 2014. Evaluation of Land Use/Land Cover Changes in East of Lake Tana, Ethiopia. *Evaluation*, 4(11).

- Gautam, M.R., Acharya, K. and Tuladhar, M.K., 2010. Upward trend of streamflow and rainfall in a small, non-snow-fed, mountainous watershed in Nepal. *Journal of hydrology*, 387(3-4), pp.304-311.
- Gebrehiwot, S.G., Gärdenäs, A.I., Bewket, W., Seibert, J., Ilstedt, U. and Bishop, K., 2014. The long-term hydrology of East Africa's water tower: Statistical change detection in the watersheds of the Abbay Basin. *Regional environmental change*, 14(1), pp.321-331.
- Gebremeskel, G. and Kebede, A., 2018. Estimating the effect of climate change on water resources: Integrated use of climate and hydrological models in the Werii watershed of the Tekeze river basin, Northern Ethiopia. *Agriculture and Natural Resources*, 52(2), pp.195-207.
- Gebremicael, T.G., Mohamed, Y.A., Betrie, G.D., van der Zaag, P. and Teferi, E., 2013. Trend analysis of runoff and sediment fluxes in the Upper Blue Nile basin: A combined analysis of statistical tests, physically-based models and landuse maps. *Journal of Hydrology*, 482, pp.57-68.
- Getachew, E., Melesse, A., 2012. The impact of land use change on the hydrology of the Angereb Watershed, Ethiopia. *International Journal of Water Sciences* 1–7.
- Gemitzi, A., Ajami, H. and Richnow, H.H., 2017. Developing empirical monthly groundwater recharge equations based on modeling and remote sensing data—Modeling future groundwater recharge to predict potential climate change impacts. *Journal of hydrology*, 546, pp.1-13.
- Givati, A., Thirel, G., Rosenfeld, D. and Paz, D., 2019. Climate change impacts on streamflow at the upper Jordan River based on an ensemble of regional climate models. *Journal of Hydrology: Regional Studies*, 21, pp.92-109.
- Gleixner, S., Keenlyside, N., Viste, E. and Korecha, D., 2017. The El Niño effect on Ethiopian summer rainfall. *Climate Dynamics*, 49(5-6), pp.1865-1883.
- Goderniaux, P., Brouyère, S., Fowler, H.J., Blenkinsop, S., Therrien, R., Orban, P. and Dassargues, A., 2009. Large scale surface–subsurface hydrological model to assess climate change impacts on groundwater reserves. *Journal of Hydrology*, 373(1-2), pp.122-138.
- Guo, S., Wang, J., Xiong, L., Ying, A. and Li, D., 2002. A macro-scale and semi-distributed monthly water balance model to predict climate change impacts in China. *Journal of Hydrology*, 268(1-4), pp.1-15.

- Guzman, J.A., Moriasi, D.N., Gowda, P.H., Steiner, J.L., Starks, P.J., Arnold, J.G. and Srinivasan, R., 2015. A model integration framework for linking SWAT and MODFLOW. *Environmental Modelling & Software*, 73, pp.103-116.
- Hagemann, S., Chen, C., Clark, D.B., Folwell, S., Gosling, S.N., Haddeland, I., Hanasaki, N., Heinke, J., Ludwig, F., Voss, F. and Wiltshire, A.J., 2013. Climate change impact on available water resources obtained using multiple global climate and hydrology models. *Earth System Dynamics*, 4(1), pp.129-144.
- Harbaugh, A.W., 2005. MODFLOW-2005, the US Geological Survey modular ground-water model: the ground-water flow process (pp. 6-A16). Reston, VA: US Department of the Interior, US Geological Survey.
- Hasan, E., Tarhule, A., Kirstetter, P.E., Clark III, R. and Hong, Y., 2018. Runoff sensitivity to climate change in the Nile River Basin. *Journal of hydrology*, 561, pp.312-321.
- Hassan, S.T., Lubczynski, M.W., Niswonger, R.G. and Su, Z., 2014. Surface-groundwater interactions in hard rocks in Sardon Catchment of western Spain: An integrated modeling approach. *Journal of hydrology*, 517, pp.390-410.
- Hashemi, H., Uvo, C.B. and Berndtsson, R., 2015. Coupled modeling approach to assess climate change impacts on groundwater recharge and adaptation in arid areas. *Hydrology and Earth System Sciences*, 19(10), pp.4165-4181.
- Hawtree, D., Nunes, J.P., Keizer, J.J., Jacinto, R., Santos, J., Rial-Rivas, M.E., Boulet, A.K., Tavares-Wahren, F. and Feger, K.H., 2015. Time series analysis of the long-term hydrologic impacts of afforestation in the Águeda watershed of north-central Portugal. *Hydrology and Earth System Sciences*, 19(7), p.3033.
- Hiscock KM (2011) Groundwater in the 21st Century – Meeting the Challenges. 207–225. doi: 10.1007/978-90-481-3426-7.
- Horsburgh, J.S. and Reeder, S.L., 2014. Data visualization and analysis within a Hydrologic Information System: Integrating with the R statistical computing environment. *Environmental modelling & software*, 52, pp.51-61.
- Huang, Y., 2014. Comparison of general circulation model outputs and ensemble assessment of climate change using a Bayesian approach. *Global and Planetary Change*, 122, pp.362-370.
- IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y .O.

- Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P. R. Mastrandrea, and L.L. White (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY , USA, 1132 pp.
- Izady, A., Davary, K., Alizadeh, A., Ziaei, A.N., Akhavan, S., Alipoor, A., Joodavi, A. and Brusseu, M.L., 2015. Groundwater conceptualization and modeling using distributed SWAT-based recharge for the semi-arid agricultural Neishaboor plain, Iran. *Hydrogeology Journal*, 23(1), pp.47-68.
- Jayasekera, D.L., Kaluarachchi, J.J. and Villholth, K.G., 2011. Groundwater stress and vulnerability in rural coastal aquifers under competing demands: a case study from Sri Lanka. *Environmental monitoring and assessment*, 176(1-4), pp.13-30.
- Jyrkama, M.I. and Sykes, J.F., 2007. The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario). *Journal of Hydrology*, 338(3-4), pp.237-250.
- Kahsay, K.D., Pingale, S.M. and Hatiye, S.D., 2018. Impact of climate change on groundwater recharge and base flow in the sub-catchment of Tekeze basin, Ethiopia. *Groundwater for Sustainable Development*, 6, pp.121-133.
- Kebede, S., Travi, Y., Alemayehu, T. and Marc, V., 2006. Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. *Journal of hydrology*, 316(1), pp.233-247.
- Kebede, S., 2010. Groundwater in Ethiopia: Occurrence, drought proofing and technology options. Addis Ababa University, Department of Earth Sciences. Retrieved on July, 10, p.2013.
- Kebede, S., 2012. Groundwater in Ethiopia: Features, numbers and opportunities. Springer Science & Business Media.
- Kidmose, J., Refsgaard, J.C., Trolborg, L., Seaby, L.P. and Escrivà, M.M., 2013. Climate change impact on groundwater levels: ensemble modelling of extreme values. *Hydrology and Earth System Sciences*, 17(4), pp.1619-1634.
- Kim, N.W., Chung, I.M., Won, Y.S. and Arnold, J.G., 2008. Development and application of the integrated SWAT–MODFLOW model. *Journal of hydrology*, 356(1-2), pp.1-16.
- Kim, U. and Kaluarachchi, J.J., 2009. Climate Change Impacts on Water Resources in the Upper Blue Nile River Basin, Ethiopia 1. *JAWRA Journal of the American Water Resources Association*, 45(6), pp.1361-1378.
- Kiesel, J., Gericke, A., Rathjens, H., Wetzig, A., Kakouei, K., Jähnig, S.C. and Fohrer, N., 2019. Climate change impacts on ecologically relevant hydrological indicators in

- three catchments in three European ecoregions. *Ecological engineering*, 127, pp.404-416.
- Kisembe, J., Favre, A., Dosio, A., Lennard, C., Sabiiti, G. and Nimusiima, A., 2019. Evaluation of rainfall simulations over Uganda in CORDEX regional climate models. *Theoretical and Applied Climatology*, 137(1-2), pp.1117-1134.
- Kling, H., Fuchs, M. and Paulin, M., 2012. Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. *Journal of Hydrology*, 424, pp.264-277.
- Koch, M. and Cherie, N., 2013. SWAT modeling of the impact of future climate change on the hydrology and the water resources in the upper Blue Nile River basin, Ethiopia. In *Proceedings of the 6th International Conference on Water Resources and Environment Research, ICWRER (Vol. 6, No. 6, pp. 488-523)*.
- Legesse, D., Vallet-Coulomb, C. and Gasse, F., 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of hydrology*, 275(1-2), pp.67-85.
- Legesse, E.S. and Beyene, B.S., 2017. Hydrology of Lake Tana Basin. In *Social and Ecological System Dynamics (pp. 117-126)*. Springer, Cham.
- Li, A., Feng, M., Li, Y. and Liu, Z., 2016. Application of Outlier Mining in Insider Identification Based on Boxplot Method. *Procedia Computer Science*, 91, pp.245-251.
- Liu, Q. and Yang, Z., 2010. Quantitative estimation of the impact of climate change on actual evapotranspiration in the Yellow River Basin, China. *Journal of Hydrology*, 395(3-4), pp.226-234.
- Lucio, P.S., Molion, L.C.B., de Avila Valadão, C., Conde, F.C., Ramos, A.M. and de Melo, M.L.D., 2012. Dynamical outlines of the rainfall variability and the ITCZ role over the West Sahel. *Atmospheric and Climate Sciences*, 2(03), p.337.
- Luo, K., Tao, F., Moiwo, J.P. and Xiao, D., 2016. Attribution of hydrological change in Heihe River Basin to climate and land use change in the past three decades. *Scientific reports*, 6, p.33704.
- Machiwal, D. and Jha, M.K., 2009. Time series analysis of hydrologic data for water resources planning and management: a review. *Journal of Hydrology and Hydromechanics*, 54(3), pp.237-257.
- Mamo, S., Ayenew, T., Berehanu, B. and Kebede, S., Hydrology of the Lake Tana Basin, Ethiopia: Implication to Groundwater-Surface Waters Interaction.

- Marx, A., Kumar, R., Thober, S., Rakovec, O., Wanders, N., Zink, M., Wood, E.F., Pan, M., Sheffield, J. and Samaniego, L., 2018. Climate change alters low flows in Europe under global warming of 1.5, 2, and 3 C. *Hydrology and Earth System Sciences*, 22(2), pp.1017-1032.
- Matalas, N.C., 1967. Autocorrelation of rainfall and streamflow minimums. US Government Printing Office.
- McCartney, M., Alemayehu, T., Shiferaw, A. and Awulachew, S., 2010. Evaluation of current and future water resources development in the Lake Tana Basin, Ethiopia (Vol. 134). IWMI.
- Meals, D.W., Spooner, J., Dressing, S.A. and Harcum, J.B., 2011. Statistical analysis for monotonic trends, Tech Notes 6, November 2011. Developed for US Environmental Protection Agency by Tetra Tech, Inc., Fairfax, VA, pp.2016-05.
- Mehari, A.K., Wondie, A., Mingist, M. and Vijverberg, J., 2014. Spatial and seasonal variation in the macro-invertebrates and physico-chemical parameters of the Enfranz River, Lake Tana sub-basin (Ethiopia). *Ecohydrology & Hydrobiology*, 14(4), pp.304-312.
- Meixner, T., Manning, A.H., Stonestrom, D.A., Allen, D.M., Ajami, H., Blasch, K.W., Brookfield, A.E., Castro, C.L., Clark, J.F., Gochis, D.J. and Flint, A.L., 2016. Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology*, 534, pp.124-138.
- Mekonnen, M.M. and Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity. *Science advances*, 2(2), p.e1500323.
- Minale, A.S. and Rao, K.K., 2011. Hydrological dynamics and human impact on ecosystems of Lake Tana, northwestern Ethiopia. *Ethiopian Journal of Environmental Studies and Management*, 4(1).
- Modarres, R. and da Silva, V.D.P.R., 2007. Rainfall trends in arid and semi-arid regions of Iran. *Journal of Arid Environments*, 70(2), pp.344-355.
- Mahmoodi, N., Wagner, P.D., Kiesel, J., and Fohrer, N., 2020. Modeling the impact of climate change on streamflow and major hydrological components of an Iranian Wadi system. (Under review).
- Morris, D.A. and Johnson, A.I., 1967. Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the US Geological Survey, 1948-60 (No. 1839-D). US Govt. Print. Off.,.



- MoWIE (Ministry of Water, Irrigation and Electricity of Ethiopian Government), 2016. Daily streamflow. Addis Ababa: The Department of Hydrology.
- Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R., 2011. Soil & Water Assessment Tool Theoretical Documentation Version 2009, Texas.
- NMA (National Meteorological Service Agency of Ethiopian Government), 2016. Daily weather data. Addis Ababa. Meteorological Data Management and Basic Climatology Case Team.
- Omondi, P.A.O., Awange, J.L., Forootan, E., Ogallo, L.A., Barakiza, R., Girmaw, G.B., Fesseha, I., Kululetera, V., Kilembe, C., Mbatia, M.M. and Kilavi, M., 2014. Changes in temperature and rainfall extremes over the Greater Horn of Africa region from 1961 to 2010. *International Journal of Climatology*, 34(4), pp.1262-1277.
- Osman, Y., Al-Ansari, N. and Abdellatif, M., 2017. Climate change model as a decision support tool for water resources management in northern Iraq: a case study of Greater Zab River. *Journal of Water and Climate Change*, p.jwc2017083.
- Park, S., Nielsen, A., Bailey, R.T., Trolle, D. and Bieger, K., 2019. A QGIS-based graphical user interface for application and evaluation of SWAT-MODFLOW models. *Environmental modelling & software*, 111, pp.493-497.
- Poppe, L., Frankl, A., Poesen, J., Admasu, T., Dessie, M., Adgo, E., Deckers, J. and Nyssen, J., 2013. Geomorphology of the Lake Tana basin, Ethiopia. *Journal of Maps*, 9(3), pp.431-437.
- Pfannerstill, M., Guse, B. and Fohrer, N., 2014. A multi-storage groundwater concept for the SWAT model to emphasize nonlinear groundwater dynamics in lowland catchments. *Hydrological processes*, 28(22), pp.5599-5612.
- Rashid, M.M., Beecham, S. and Chowdhury, R.K., 2015. Assessment of trends in point rainfall using continuous wavelet transforms. *Advances in water resources*, 82, pp.1-15.
- R Core Team, 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.
- Rientjes, T.H.M., Perera, B.U.J., Haile, A.T., Reggiani, P. and Muthuwatta, L.P., 2011. Regionalisation for lake level simulation-the case of Lake Tana in the Upper Blue Nile, Ethiopia. *Hydrology and Earth System Sciences*, 15(4), p.1167.
- Rodell, M., Velicogna, I. and Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. *Nature*, 460(7258), p.999.

- Roth, V., Lemann, T., Zeleke, G., Subhatu, A.T., Nigussie, T.K. and Hurni, H., 2018. Effects of climate change on water resources in the upper Blue Nile Basin of Ethiopia. *Heliyon*, 4(9), p.e00771.
- Saha, G.C., Li, J., Thring, R.W., Hirshfield, F. and Paul, S.S., 2017. Temporal dynamics of groundwater-surface water interaction under the effects of climate change: A case study in the Kiskatinaw River Watershed, Canada. *Journal of Hydrology*, 551, pp.440-452.
- Sear, D.A., Armitage, P.D. and Dawson, F.H., 1999. Groundwater dominated rivers. *Hydrological Processes*, 13(3), pp.255-276.
- Sena, C. and de Melo, M.T.C., 2012. Groundwater–surface water interactions in a freshwater lagoon vulnerable to anthropogenic pressures (Pateira de Fermentelos, Portugal). *Journal of hydrology*, 466, pp.88-102.
- Setegn, S.G., Srinivasan, R. and Dargahi, B., 2008. Hydrological modelling in the Lake Tana Basin, Ethiopia using SWAT model. *The Open Hydrology Journal*, 2(1).
- Setegn, S.G., Rayner, D., Melesse, A.M., Dargahi, B. and Srinivasan, R., 2011. Impact of climate change on the hydroclimatology of Lake Tana Basin, Ethiopia. *Water Resources Research*, 47(4).
- Seyoum, M., van Andel, S.J., Xuan, Y. and Amare, K., 2013. Rainfall forecasts for rainfall runoff predictions. A case study in poorly gauged Ribb and Gumara catchments, upper Blue Nile, Ethiopia. *Physics and Chemistry of the Earth, Parts A/B/C*, 61, pp.43-51.
- Shao, G., Zhang, D., Guan, Y., Xie, Y. and Huang, F., 2019. Application of SWAT model with a modified groundwater module to the semi-arid Hailu River Catchment, Northwest China. *Sustainability*, 11(7), p.2031.
- Sophocleous, M., 2002. Interactions between groundwater and surface water: the state of the science. *Hydrogeology journal*, 10(1), pp.52-67.
- Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L., Van Lanen, H., Sauquet, E., Demuth, S., Fendekova, M. and Jordar, J., 2010. Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences*, 14, pp.p-2367.
- Stegen, J.C., Fredrickson, J.K., Wilkins, M.J., Konopka, A.E., Nelson, W.C., Arntzen, E.V., Chrisler, W.B., Chu, R.K., Danczak, R.E., Fansler, S.J. and Kennedy, D.W., 2016. Groundwater–surface water mixing shifts ecological assembly processes and stimulates organic carbon turnover. *Nature communications*, 7, p.11237.

- Sutanudjaja, E.H., Van Beek, L.P.H., De Jong, S.M., van Geer, F.C. and Bierkens, M.F.P., 2011. Large-scale groundwater modeling using global datasets: a test case for the Rhine-Meuse basin. *Hydrology and Earth System Sciences*, 15, pp.2913-2935.
- Tarhule, A., 2017. The future of water: Prospects and challenges for water management in the 21st century. In *Competition for Water Resources* (pp. 442-454). Elsevier.
- Taye, M.T., Ntegeka, V., Ogiramo, N.P. and Willems, P., 2011. Assessment of climate change impact on hydrological extremes in two source regions of the Nile River Basin. *Hydrology and Earth System Sciences*, 15(1), pp.209-222.
- Taye, M.T., Willems, P. and Block, P., 2015. Implications of climate change on hydrological extremes in the Blue Nile basin: A review. *Journal of Hydrology: Regional Studies*, 4, pp.280-293.
- Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M. and Konikow, L., 2013. Ground water and climate change. *Nature climate change*, 3(4), p.322.
- TBDA (Tana Basin Development Authority), (2016. Inventory data of pre-existing water scheme (Boreholes, hand-dug wells, and spring) of the Lake Tana Basin. Bahir Dar, Ethiopia.
- Tegegne, G., Hailu, D. & Aranganathan, S.M., 2013. Lake Tana Reservoir Water Balance Model. *International Journal of Application or Innovation in Engineering & Management (IJAIEEM)*, 2(3), pp.474–478. Available at: [www.ijaiem.org](http://www.ijaiem.org).
- Tekleab, S., Mohamed, Y. and Uhlenbrook, S., 2013. Hydro-climatic trends in the Abay/upper Blue Nile basin, Ethiopia. *Physics and Chemistry of the Earth, Parts A/B/C*, 61, pp.32-42.
- Tesemma, Z.K., Mohamed, Y.A. and Steenhuis, T.S., 2010. Trends in rainfall and runoff in the Blue Nile Basin: 1964–2003. *Hydrological processes*, 24(25), pp.3747-3758.
- Tesfaye, S., Taye, G., Birhane, E. and van der Zee, S.E., 2019. Observed and model simulated twenty-first century hydro-climatic change of Northern Ethiopia. *Journal of Hydrology: Regional Studies*, 22, p.100595.
- Teshome, M., 2016. Farmers' vulnerability to climate change-induced water poverty in spatially different agro-ecological areas of northwest Ethiopia. *Journal of Water and Climate Change*, 7(1), pp.142-158.

- Tigabu T. B., Hörmann G., Wagner P. D., Fohrer N., 2018. Statistical analysis of rainfall and streamflow time series in Lake Tana Basin, Statistical analysis of rainfall and streamflow time series in Lake Tana Basin ,. *Journal of Water and Climate Change*.
- Tigabu T. B., Wagner P. D., Hörmann G., Fohrer N., 2019. Modelling the impact of agricultural crops on the spatial and seasonal variability of water balance components in the Lake Tana Basin, Ethiopia. *Hydrology Research*, 50 (5), pp.1376-1395.
- Toews, M.W. and Allen, D.M., 2009. Simulated response of groundwater to predicted recharge in a semi-arid region using a scenario of modelled climate change. *Environmental Research Letters*, 4(3), p.035003.
- Thomas, B.E. and Pool, D.R., 2006. Trends in streamflow of the San Pedro River, southeastern Arizona, and regional trends in rainfall and streamflow in southeastern Arizona and southwestern New Mexico. US Department of the Interior, US Geological Survey.
- UNICEF (United Nations Children's Fund), 2016. Ethiopia El Nino Emergency. In: Fast Facts. <https://reliefweb.int/report/ethiopia/ethiopia-el-ni-o-emergency-fast-facts-june-2016>.
- USGS (US Geological Survey), 2016. Shuttle Radar Topography Mission (SRTM) 1 arc-second global Digital Elevation Model (DEM), USGS EarthExplorer, <http://earthexplorer.usgs.gov>), accessed 24 January 2016.
- Venkataraman, K., Tummuri, S., Medina, A. and Perry, J., 2016. 21st century drought outlook for major climate divisions of Texas based on CMIP5 multimodel ensemble: Implications for water resource management. *Journal of hydrology*, 534, pp.300-316.
- Wagner, P.D., Reichenau, T.G., Kumar, S. and Schneider, K., 2015. Development of a new downscaling method for hydrologic assessment of climate change impacts in data scarce regions and its application in the Western Ghats, India. *Regional environmental change*, 15(3), pp.435-447.
- Wagner, P.D., Bhallamudi, S.M., Narasimhan, B., Kantakumar, L.N., Sudheer, K.P., Kumar, S., Schneider, K. and Fiener, P., 2019. Dynamic integration of land use changes in a hydrologic assessment of a rapidly developing Indian catchment. *Science of the Total Environment*, 539, pp.153-164.
- Wagner, P.D. and Waske, B., 2016. Importance of spatially distributed hydrologic variables for land use change modeling. *Environmental Modelling & Software*, 83, pp.245-254.

- Wagner, P.D., Hörmann, G., Schmalz, B., Fohrer, N., 2018. Characterisation of the water and nutrient balance in the rural lowland catchment of the Kielstau. *Hydrologie & Wasserbewirtschaftung*, 62(3), 145-158.
- Wickham, H., 2007. Reshaping Data with the reshape Package. *Journal of Statistical Software*, 21(12), 1-20. URL <http://www.jstatsoft.org/v21/i12/>.
- Wickham, H., 2011. ggplot2. *Wiley Interdisciplinary Reviews: Computational Statistics*, 3(2), pp.180-185.
- Wickham H., Hester J. and Francois R. 2017. readr: Read Rectangular Text Data. R package version 1.1.1. <https://CRAN.R-project.org/package=readr>.
- Wickham, H., 2018. stringr: Simple, Consistent Wrappers for Common String Operations. R package version 1.3.1. <https://CRAN.R-project.org/package=stringr>.
- Wickham, H., Francois, R. and Henry, L., 2018. Müller, K. dplyr: A Grammar of Data Manipulation. R package version 0.7. 6
- Woldeamlak, S.T., Batelaan, O. and De Smedt, F., 2007. Effects of climate change on the groundwater system in the Grote-Nete catchment, Belgium. *Hydrogeology Journal*, 15(5), pp.891-901.
- Woldesenbet, T.A., Elagib, N.A., Ribbe, L. and Heinrich, J., 2017. Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia. *Science of The Total Environment*, 575, pp.724-741.
- Woldesenbet, T.A., Elagib, N.A., Ribbe, L. and Heinrich, J., 2018. Catchment response to climate and land use changes in the Upper Blue Nile sub-basins, Ethiopia. *Science of the total environment*, 644, pp.193-206.
- World Bank, 2006. Ethiopia: Managing water resources to maximize sustainable growth.
- Worqlul, A.W., Collick, A.S., Rossiter, D.G., Langan, S. and Steenhuis, T.S., 2015. Assessment of surface water irrigation potential in the Ethiopian highlands: The Lake Tana Basin. *Catena*, 129, pp.76-85.
- WWAP (UNESCO World Water Assessment Programme), 2019. The United Nations World Water Development Report 2019: Leaving No One Behind.
- Xu, C.Y., 1999. Climate change and hydrologic models: A review of existing gaps and recent research developments. *Water Resources Management*, 13(5), pp.369-382.
- Yimer, G., Jonoski, A. and Griensven, A.V., 2009. Hydrological response of a catchment to climate change in the upper Beles river basin, Upper Blue Nile, Ethiopia. *Nile Basin Water Engineering Scientific Magazine*, 2, pp.49-59.

Zhou, Y. and Li, W., 2011. A review of regional groundwater flow modeling. *Geoscience frontiers*, 2(2), pp.205-214.

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## Declarations

M.Sc. Tibebe Belete Tigabu

Statutory Declaration:

Herewith I declare on oath that the submitted dissertation under the title “Water Resources in Lake Tana Basin: Analysis of hydrological time series data and impact of climate change with emphasis on groundwater, Upper Blue Nile Basin, Ethiopia” has been authored independently and without illegitimate external help and that it has not been formerly submitted to another university department.

Kiel, 02.04.2020

Signature



Herewith I declare, that I am not subject to any pending case of public prosecution.

Kiel, 02.04.2020

Signature



Herewith I declare, that the dissertation complies with the conventions of proper academic practices as defined by the DFG.

Kiel, 02.04.2020)

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### Declaration of co-authorship

If a dissertation is based on already published or submitted co-authored articles, a declaration from each of the authors regarding the part of the work done by the doctoral candidate must be enclosed when submitting the dissertation.

#### 1. Doctoral candidate

**Name:** Tibebe Belete Tigabu

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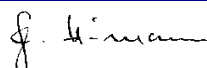
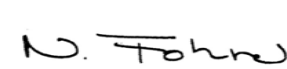

Tigabu, T.B., Hörmann, G., Wagner, P.D. and Fohrer, N., 2020. Statistical analysis of rainfall and streamflow time series in the Lake Tana Basin, Ethiopia. Journal of Water and Climate Change, 11(1), pp.258-273.

The extent of the doctoral candidate's contribution to the article is assessed on the following scale:

- A. Has contributed to the work (0-33%)
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3. Declaration on the individual phases of the scientific work (A,B,C)	Extent
<b>Concept:</b> Formulation of the basic scientific problem based on theoretical questions which require clarification, including a summary of the general questions which, it is assumed, will be answerable via analyses or concrete experiments/investigations	<b>C</b>
<b>Planning:</b> Planning of experiments/analyses and formulation of investigative methodology, including choice of method and independent methodological development, in such a way that the scientific questions asked can be expected to be answered	<b>C</b>
<b>Execution:</b> Involvement in the analysis or the concrete experiments/investigation	<b>C</b>
<b>Manuscript preparation: Presentation, interpretation and discussion of the results obtained in article form</b>	<b>C</b>

#### 4. Signature of all co-authors

Date	Name	Signature
30.3.2020	Georg Hörmann	
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30.03.2020	Tibebe B. Tigabu	

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If a dissertation is based on already published or submitted co-authored articles, a declaration from each of the authors regarding the part of the work done by the doctoral candidate must be enclosed when submitting the dissertation.

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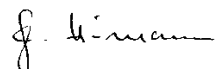


Tigabu, T.B., Wagner, P.D., Hörmann, G. and Fohrer, N., 2019. Modeling the impact of agricultural crops on the spatial and seasonal variability of water balance components in the Lake Tana basin, Ethiopia. Hydrology Research, 50(5), pp.1376-1396.

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- C. Did the majority of the work independently (67-100%)

3. Declaration on the individual phases of the scientific work (A,B,C)	Extent
<b>Concept:</b> Formulation of the basic scientific problem based on theoretical questions which require clarification, including a summary of the general questions which, it is assumed, will be answerable via analyses or concrete experiments/investigations	<b>C</b>
<b>Planning:</b> Planning of experiments/analyses and formulation of investigative methodology, including choice of method and independent methodological development, in such a way that the scientific questions asked can be expected to be answered	<b>C</b>
<b>Execution:</b> Involvement in the analysis or the concrete experiments/investigation	<b>C</b>
<b>Manuscript preparation: Presentation, interpretation and discussion of the results obtained in article form</b>	<b>C</b>

#### 4. Signature of all co-authors

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31.3.2020	Nicola Fohrer	
30.3.2020	Paul D Wagner	

#### 5. Signature of doctoral candidate

Date	Name	Signature
30.03.2020	Tibebe B. Tigabu	

### Declaration of co-authorship

If a dissertation is based on already published or submitted co-authored articles, a declaration from each of the authors regarding the part of the work done by the doctoral candidate must be enclosed when submitting the dissertation.

#### 1. Doctoral candidate

**Name:** Tibebe Belete Tigabu

#### 2. This co-author declaration applies to the following article:

Tigabu, T.B., Wagner, P.D, Hörmann, G. and Fohrer, N., 2020. Modelling spatio-temporal flow dynamics of groundwater-surface water interactions of the Lake Tana Basin, Upper Blue Nile, Ethiopia, Under review

The extent of the doctoral candidat's contribution to the article is assessed on the following scale:

- A. Has contributed to the work (0-33%)
- B. Has made a substantial contribution (34-66%)
- C. Did the majority of the work independently (67-100%)

#### 3. Declaration on the individual phases of the scientific work (A,B,C)

**Extent**

**Concept:** Formulation of the basic scientific problem based on theoretical questions which require clarification, including a summary of the general questions which, it is assumed, will be answerable via analyses or concrete experiments/investigations

**C**

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**C**

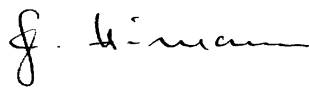

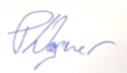
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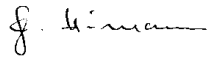


Tibebe B. Tigabu<sup>1</sup>, Paul D. Wagner, Georg Hörmann, Jens Kiesel and Nicola., 2020. Climate change impacts on the water and groundwater resources of the Lake Tana Basin, Ethiopia, To be submitted.

The extent of the doctoral candidate's contribution to the article is assessed on the following scale:

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